UNIVERSITAT JAUME I
UNIVERSITAT JAUME I (CASTELLÓ)
DEPARTAMENT D'ENGINYERIA
MECÀNICA I CONSTRUCCIÓ

CONTRIBUTION TO HAND FUNCTIONAL ASSESSMENT BASED ON ITS KINEMATICS

A thesis submitted in the fulfillment of the requirements for the degree of Doctor of Philosophy with international mention

Author:
Verónica Gracia Ibáñez

Supervisors:
Dr. Margarita Vergara Monedero
Dr. Joaquín L. Sancho Bru

Castelló (Spain), December 2016

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A Héctor i Pedro que són ma vida
i a ma mare que ho va ser

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I per últim, a la família que sempre està ahí, i als amics.

ABSTRACT

The aim of the thesis, which is the outcome of the investigations in which I have participated within the Biomechanics and Ergonomics group of the Universitat Jaume I, is the achievement of practical contributions to the functional assessment of the hand based on its kinematics. It is presented as a compendium of published or in revision works, one per chapter, each corresponding to a contribution itself to the problem.

First, a critical literature review on the functional assessment of the hand oriented to the activities of daily living (ADL) is done in the thesis. It is observed that the assessment methods used tend to be highly subjective, and in addition they are often valid for only certain pathologies. There are general and objective methods, like measuring grip strength or active range of motion (AROM), however the relationship between them and the functionality is still subject of research. Consequently, the goal of the thesis is focused in the pursuit of general and objective methods for functional assessment of the hand. And given the magnitude of the problem, it is limited to the kinematic analysis. In order to define functionality, the WHO's International Classification of Functioning, Disability and Health is taken as a reference, universally accepted and valid for the assessment on health issues.

The first practical contribution consists in a rating of the different grasp types according to their relevancy for personal autonomy. It can be applied both in functional assessment, in rehabilitation or in clinic decision-making.

By means of using a videogrammetric technique, the interrelationship between the ranges of flexion and extension of the metacarpophalangeal (MCP) joint of the fingers and the posture of the adjacent MCP joints is quantified. Equations for estimating these ranges of motion are also provided. They can be used in improving existing biomechanical models, but may also be useful in checking abnormalities in pathological hands.

Given the problems arising from the usage of the videogrammetric technique for recording the hand kinematics in ADL, a new calibration method for an instrumented glove that requires the registration of just one simple reference posture is proposed. The recording of the kinematics of the hand in ADL by using this protocol is feasible and accurate, being in addition suitable for its use in pathological subjects.

The mentioned protocol is used to record the functional ranges of motion of the hand joints (except the distal interphalangeal ones). These functional ranges of motions are compared with the AROM, being observed higher values in AROM generally. Furthermore, data are provided that allow inferring the level of functionality in relation to the recovered AROM.

Finally, the use of principal component analysis (PCA) to identify parameters to be used in functional assessment is proposed in the thesis. The statistics from the recording of postures of a healthy sample while performing ADL, expressed on the base of the components obtained when applying PCA, along with their temporal derivatives, are presented. These statistics would be representative of the functionality of the healthy hand, and their comparison with the ones registered to two pathological subjects while performing the same ADL, allowed obtaining information from the functional impairment of each of these subjects in higher detail than from the information obtained from using classical methods. It is a preliminary study; however the promising results open an interesting via.

RESUM

L’objectiu de la tesi, fruit de les investigacions en què he participat dins el grup de Biomecànica i Ergonomia de la Universitat Jaume I, és la realització d’aportacions pràctiques a l’avaluació funcional de la mà en base a la seva cinemàtica. Es presenta com a compendi de treballs publicats o en revisió, un per capítol, corresponent-se cadascun d’ells amb una aportació en sí mateixa al problema.

A la tesi es realitza en primer lloc una revisió bibliogràfica crítica de l’avaluació funcional de la mà orientada a les activitats de la vida diària (AVD). S’observa que els mètodes d’avaluació emprats solen ser força subjectius, i sovint vàlids sols per a determinades patologies. Existeixen alguns mètodes generals i objectius com la mesura de la força de prensió o de rangs actius de moviment (RAM), no obstant això, la relació existent entre ells i la funcionalitat encara és objecte d’estudi. Com a conseqüència, l’objectiu de la tesi es centra en la recerca de mètodes objectius i generals d’avaluació funcional de la mà. I atesa la magnitud del problema, es limita a l’anàlisi cinemàtica. Per a la definició de funcionalitat es pren com a referència, universalment acceptada i vàlida per a valoració en temes de salut, la Classificació Internacional del Funcionament, de la Discapacitat i de la Salut (CIF) de la OMS.

La primera contribució pràctica consisteix en la gradació dels diferents tipus de prensió en relació a la seva rellevància per a l’autonomia personal, que pot ser d’aplicació per a la valoració funcional i també en rehabilitació o en la presa de decisions clíniques.

Mitjançant l’ús de la tècnica videogramètrica es quantifica la interrelació entre els rangs de flexo-extensió de l’articulació metacarpofalàngica (MCF) dels dits i la postura de les articulacions MCF adjacents. Es proporcionen així mateix les equacions que permeten estimar aquests rangs de moviment per al seu ús en la millora dels models biomecànics existents, però que podrien també ser d’utilitat en la detecció d’anormalitats en mans patològiques.

Degut als problemes que suposa l’ús de la tècnica videogramètrica per al registre de la cinemàtica de la mà en AVD, es proposa un nou mètode de calibratge per a guant instrumentat que requereix el registre d’una única postura de referència. L’enregistrament de la cinemàtica de la mà en AVD mitjançant aquest protocol és factible i precís, a més de ser adequat per a l’ús en subjectes patològics.

Aquest protocol s’utilitza per a mesurar els rangs funcionals de les articulacions de la mà (excepte les interfalàngiques distals). Aquests rangs funcionals es comparen amb els RAM, observant-se en general majors valors de RAM. Així mateix, s’aporten

dades que permeten inferir el grau de funcionalitat en funció del grau de RAM recuperat.

Per últim, en la tesi es proposa l'ús de l'anàlisi de components principals (ACP) per a la identificació de paràmetres a utilitzar en l'avaluació funcional. Es presenten els estadístics de l'enregistrament de postures d'una mostra de subjectes sans realitzant AVD, expressades en base als factors obtingutsen aplicar ACP, així com de les seves derivades temporals. Aquests estadístics serien representatius de la funcionalitat de la ma sana i la seva comparació amb els enregistrats a dos subjectes patològics realitzant eixes AVD ha permès obtenir informació de l'afectació funcional de cadascun dels subjectes, i amb major nivell de detall que la informació que s'obté de la utilització dels mètodes clàssics. Tot i ser aquest un estudi preliminar, els prometedors resultats obrin una via interessant.

RESUMEN

El objetivo de esta tesis, fruto de las investigaciones en que he participado en el grupo de Biomecánica y Ergonomía de la Universitat Jaume I, es la realización de aportaciones prácticas a la evaluación funcional de la mano en base a su cinemática. Se presenta como un compendio de trabajos publicados o en revisión, uno por capítulo, correspondiéndose cada uno con una aportación en sí misma al problema.

En la tesis se realiza en primer lugar una revisión bibliográfica crítica sobre la evaluación funcional de la mano orientada a las actividades de la vida diaria (AVD). Se observa que los métodos de evaluación empleados suelen ser altamente subjetivos, y a menudo válidos sólo para determinadas patologías. Existen algunos métodos generales y objetivos como la medición de fuerza de agarre o de rangos activos de movimiento (RAM), no obstante la relación existente entre los mismos y la funcionalidad aún es objeto de estudio. Como consecuencia, se centra el objetivo de la tesis en la búsqueda de métodos objetivos y generales de evaluación funcional de la mano. Y dada la magnitud del problema, se limita al análisis cinemático. Para la definición de funcionalidad se toma como referencia, universalmente aceptada y válida para valoración en temas de salud, la Clasificación Internacional del Funcionamiento, de la Discapacidad y de la Salud (CIF) de la OMS.

La primera contribución práctica consiste en la gradación de los diferentes tipos de agarre en relación a su relevancia para la autonomía personal, que puede ser de aplicación tanto para valoración funcional como en rehabilitación o en la toma de decisiones clínicas.

Mediante el uso de una técnica videogramétrica se cuantifica la interrelación entre los rangos de flexo-extensión de la articulación metacarpofalángica (MCF) de los dedos y la postura en las articulaciones MCF adyacentes. Se proporcionan asimismo las ecuaciones que permiten estimar estos rangos de movimiento para su uso en la mejora de los modelos biomecánicos existentes, pero que podrían ser también de utilidad en la detección de anormalidades en manos patológicas.

Dados los problemas que supone el uso de la técnica videogramétrica para el registro de la cinemática de la mano en AVD, se propone un nuevo método de calibración para guante instrumentado que requiere el registro de una única postura de referencia. El registro de la cinemática de la mano en AVD mediante este protocolo es factible y preciso, siendo además adecuado para su uso en sujetos patológicos.

Dicho protocolo se utiliza para medir los rangos funcionales de las articulaciones de la mano (salvo las interfalangicas distales). Estos rangos funcionales se comparan con los rangos activos de movimiento (RAM), observándose en general mayores

valores de RAM. Asimismo se aportan datos que permiten inferir el grado de funcionalidad en función del RAM recuperado.

Por último, en la tesis se propone el uso del análisis de componentes principales (ACP) para la identificación de parámetros a utilizar en la evaluación funcional. Se presentan los estadísticos del registro de posturas de una muestra de sujetos sanos realizando AVD, expresadas en base a los factores obtenidos al aplicar ACP, así como de sus derivadas temporales. Dichos estadísticos serían representativos de la funcionalidad de la mano sana, y su comparación con los registrados a dos sujetos patológicos realizando dichas AVD ha permitido obtener información de la afectación funcional de cada uno de los sujetos, y con mayor nivel de detalle que la información que se obtiene de utilizar los métodos clásicos. Es un estudio preliminar, pero los prometedores resultados abren una interesante vía.

INDEX

Introduction

ABBREVIATIONS

ADL:	Activities of daily living
AROM:	Active range of motion
CMC:	Carpometacarpal
DoF:	Degrees of freedom
FROM:	Functional range of motion
ICF:	International classification of functioning, disability and health
IP:	Interphalangeal
MCP:	Metacarpophalangeal
MoCap:	Motion capture
PCA:	Principal component analysis
PIP:	Proximal interphalangeal
WHO:	World Health Organization

AIM

The methods currently used to assess hand functionality are highly subjective (Meiners et al. 2002; De Los Reyes-Guzmán et al. 2014), as evidenced also in this thesis. Furthermore, many of them are specific for certain diseases (Lemmens et al. 2012; Metcalf et al. 2007; Moore et al. 2014). Hand kinematics might be used for a general and more objective assessment (van Dokkum et al. 2014), as it plays an important role in hand function (Tsai et al. 2016). However, the large number of degrees of freedom (DoF) of the hand makes the functional kinematic characterization of the hand challenging (Coupier et al. 2016). Principal component analysis (PCA) is a generally-applicable method to simplify systems with a high number of DoF, and could be used to make the kinematics characterization of the hand affordable in this search for a more general and objective assessment of hand function. Hence, the purpose of this thesis is to contribute to the functional assessment of the hand based on its kinematic characterization, providing more objectivity and general applicability to different pathologic populations. Specifically, the following objectives were pursued, with objectives 2 to 6 identified from the review established as 1st objective:

1. Critical review of hand function assessment
2. Establishment of a rating of the relevancy of the different grasp types for functionality.
3. Quantification of the kinematical interdependencies of the maximal ranges of flexion and extension at the metacarpophalangeal (MCP) joints.
4. Development of a protocol to measure hand kinematics in activities of daily living (ADL), accurate enough and suitable for injured hands.

5. Identification of the relationship between functional and active ranges of motion of the hand joints.
6. Analysis of the feasibility of using PCA as a tool for functional hand assessment.

CONTEXT

The idea originates from the research carried out within the research group of *Biomechanics & Ergonomics* at the Universitat Jaume I (Castellón – Spain) of which I am a member since January 2014. The thesis is framed within two research projects funded by different public entities, and it is worth mentioning that throughout the development of this thesis I came into contact with different professionals involved in the functional evaluation of the hand as well as with different companies in order to gain practical understanding of the problem. Finally, in the last period of the thesis development I made an abroad research stay with the goal of delving into the goodness of the methodology proposed in the thesis by means of testing it on patients.

Research group

The research fields of the *Biomechanics & Ergonomics Group* cover biomechanics of the foot and the knee, emotional design, dental biomechanics, ergonomics of hand tools and biomechanics of the human hand. Focusing on the human hand, the group has an extensive background in knowledge, both from an ergonomic and a biomechanical point of view. This research line started with the development of a scalable three-dimensional model of the hand. Originally, the model was thought to be used for the ergonomic design of hand tools, but later it was also used for medical simulation. A better understanding of the human hand can be applied in surgery to improve clinical decision-making, in disability assessment, or in rehabilitation to select the best strategy for the best possible recovering of a pathologic or injured hand. Under this premise, the research line drifted into a better understanding of how the human grasp occurs, and more specifically in ADL. Also, lately the group has started to apply its knowledge to the design and evaluation of anthropomorphic hands. Nevertheless, the work presented in this thesis is focused on achieving a better knowledge of the behaviour of the human hand with medical and rehabilitation purposes. More specifically, it is aimed to contribute to the functional kinematic characterization of the human hand. Although the direct application of the results is on the functional assessment, they could be also applied to the design of products for daily functionality, or to the design of hand prostheses.

Research projects

This thesis is part of two research projects, in which I am participating as a researcher (Table 0.1), that are funded by different public institutions.

Table 0. 1. Research projects where the Thesis is framed in

Research projects where the Thesis is framed in.		
1	Reference	P1-1B2014-10
	Tittle	Characterization of kinematic synergies of the hand in activities of daily living oriented to functional assessment
	Institution	Universitat Jaume I
	Period	2015-2017 (3 years)
	Funding	28 406.00 €
	Main Researcher	Margarita Vergara Monedero
	Research Group	Francisco Javier Andrés de la Esperanza
		Marta Covadonga Mora Aguilar
		Verónica Gracia Ibáñez
2	Reference	DPI2014-52095-P
	Tittle	Kinematic characterization of the hand aimed to functional assessment of products in activities of daily living
	Institution	Ministry of Economy and Competitiveness
	Period	2015-2017 (3 years)
	Funding	95 000.00 €
	Main Researchers	Joaquín Luis Sancho Bru
		Margarita Vergara Monedero
	Research Group	Verónica Gracia Ibáñez
		Néstor José Jarque Bou
		Wendy M. Murray

Collaborations with external companies

Health professionals —including medical rehabilitation orthopaedists, medical evaluators and physiotherapists— are the ones who can best transfer their experience and insights regarding how the functional assessments are carried out in practice. Therefore, contacts with different companies in the field of health were established (Table 0.2). They ranged from public hospitals to private companies, including a Mutual insurance company, 'Union de Mutuas', which is a private company collaborating with the Social Security public service. Noteworthy is the 3 years collaboration agreement signed with this company, which helped me in testing the methodology proposed of using PCA as a tool for functional assessment in two patients (Chapter 6). Also, the private company "BAASYS" acted as Promoter-Observer Entity in both research projects that frame the thesis. Beyond the two pathological subjects analyzed in this thesis, and given the promising results obtained with the proposed methodology, the collaboration agreements and contacts performed will allow applying the methods to more pathological subjects in future research.

From these visits, I could learn by experience in:

1. Functional assessment in practice, mainly through several visits to the facilities of Union de Mutuas and BAASYS.

Table 0. 2. List of Institutions/Companies visited

	Name of the Company/Institution	Type & Description of the Company/Institution	Persons attending
1	Disabled orientation & assessment Center of the Department of Social Welfare	Public system for the official assessment of disability in our region belonging to the Ministry of Health & Social Services	Head of section in our region
2	"Union de Mutuas" Mutual insurance company*	Private enterprise with agreement with public administration aimed to the management of economic health benefits (medical care) and economic benefits (payment of sick leave) in cases of occupational accident and or occupational disease.	Medical department heads in rehabilitation and functional assessment in our region
3	"BAASYS"	Private company aimed to biomechanical studies applied to the diagnosis of pathologies and functional assessment of musculoskeletal system	Technical medical director
4	"Clínica Granell" Physiotherapy Clinic	Private company aimed to the application of physiotherapy, osteopathy and sports rehabilitation.	Physioterapist Director of the Clinic
5	"Hospital Provincial de Castellón"	Public hospital of the County council of Castellón	Physioterapist of the service of physiotherapy and occupational therapy

2. Disability appraisal, through the visits to the public system for the official assessment of disability. These visits allowed identifying how the regulations in force are being applied by the government in our country, which is described in chapter 1.

3. Hand assessment with rehabilitation purposes, especially through the visits to Union de Mutuas, to the private physiotherapy clinic Granell, and to the facilities of physiotherapy of the Hospital Provincial de Castellon. The research stay made abroad allowed us to check the similarity of the procedures currently used for functional assessment in France and Spain.

Research stay

In the fulfilment of the requirements for applying for an international mention in my PhD, I performed a 3 months research stay in the Euromov Institute, at University of Montpellier, under the supervision of Pr. Isabelle Laffont & Pr. Denis Mottet. Euromov is the "Centre européen du recherche de le mouvement humain", which collaborates with different hospitals: the University Hospital Center of Montpellier (Lapeyronie Hospital) and the University Hospital Center of Nîmes (Rehabilitation Hospital at Le Grau du Roi).

The research project developed during the stay was entitled "Applying principal component analysis for hand kinematic assessment in stroke patients with rehabilitation purposes". The main idea was to test the methodology proposed in chapter 6 to assess the kinematic functionality of the hand. A small number of the activities, selected within the ones of the proposed methodology, were performed by patients while they were wearing the Cyberglove. Clinical assessments, including Fugl Meyer test, Box & Block test and Nine-hole peg test, were also obtained as reference to check the methodology. Furthermore, a prospective experiment was carried out: five movements trying to be representative of the synergies underlying the healthy performance of ADL were tested both in patients and in healthy people. However, the results from this research stay are not included in this thesis. The data are now being analyzed.

STRUCTURE

Since the research process has led to the development of several productive experiments and results, this thesis is written as a compendium of publications generated. The structure of chapters of this thesis, along with the references of publications, is detailed in Table 0.3. Chapter 1 is a book chapter already published. Chapters 2-5 are articles published or in review in different journals. Chapter 6 is a communication presented in a congress.

The revision of the state of art, along with the sighting of the real current situation, is reflected in chapter 1. From this revision, the problem to be faced was constrained to the functionality assessment of the hand through the kinematic evaluation during the performance of ADL from the ICF. Two different approaches were used: First, a qualitative approach through the analysis of videos to look for the most relevant grasps for autonomy used in ADL, and second, a quantitative approach by characterizing the kinematics of the healthy hand while performing ADL, to be compared with pathological hands. For the qualitative approach, an experiment was carried out (1st experiment), whose results are reflected in chapter 2. For the second approach, 3 additional experiments were performed, which led to chapters 3 to 6. Chapter 3 shows the analysis of the kinematic interdependencies existing in the maximum ranges of flexion and extension of the hand joints (2nd experiment). This experiment combines the demonstration of synergies of the hand due to its physical structure, the measurement of active range of motion (AROM) and the use of a videogrammetric technique with good accuracy but with many hiding problems. Chapter 4 is the result of searching for suitable devices of motion capture (MoCap) of the hand during the development of ADL. While readying a dataglove (to avoid hiding problems of videogrametric techniques) the need for a suitable calibration arose, and it was checked that using an across-subject calibration allows measuring the hand posture recording just one easy reference posture to each subject (3rd experiment). Once such measuring protocol was defined, the main purpose of the thesis could be tackled, the functional kinematic characterization of the healthy hand, which led to chapters 5 & 6 (4th experiment). A more detailed description of each chapter follows.

Table 0. 3. List of chapters and their correspondent publications. *Last update of Status: 30th of november 2016

Chapter	Tittle – Authors	Publication & Status*	Authors
	Review. State of art: Functional Hand Assessment		
1	**Evaluation of hand functionality during Activities of Daily Living (ADL). A review**	Activities of Daily Living (ADL): Cultural Differences, Impacts of Disease and Long-term Health Effects, edited by S. T. Lively. New York: Nova Science Pub Inc, 2015, pp. 103–132	M. Vergara, V. Gracia-Ibáñez, J.L. Sancho-Bru
	First approach-qualitative (first contribution to functional hand assessment)		
2	**Relevancy of grasp types to assess functionality for personal autonomy**	Article pending editor's decision after minor changes for its publication in Journal of Hand Therapy	V. Gracia-Ibáñez, M. Vergara, J.L. Sancho-Bru
	Hand synergies		
3	**Interdependency of the maximum range of flexion-extension of hand metacarpophalangeal joints**	Computer Methods in Biomechanics and Biomedical Engineering, 2016, p. 1-8. doi: http://dx.doi.org/ 10.1080/ 10255842.2016.1189541.	V. Gracia-Ibáñez, M. Vergara, J.L. Sancho-Bru
	Current devices to record kinematics		
4	**Across-subject calibration of an instrumented glove to measure hand movement for clinical purposes**	Article accepted for publication in Computer Methods in Biomechanics and Biomedical Engineering	V. Gracia-Ibáñez, M. Vergara, J. H. Buffi, W. M. Murray, J- L. Sancho-Bru
	Second approach – Functional ROM vs AROM		
5	**Functional Range of Motion of the Hand Joints in activities of the International Classification of Functioning, Disability and Health (ICF)**	Article accepted for publication in Journal of Hand Therapy	V. Gracia-Ibáñez, M. Vergara, J-L Sancho-Bru, M-C. Mora, C. Piqueras
	Third approach - Principal Component Analysis to assess functionality		
6	**Evaluación funcional de la mano mediante reducción dimensional de su cinemática (Functional assessment of the hand by dimensional reduction of its kinematics)**	Article in XXI Congreso Nacional de Ingeniería Mecánica	V. Gracia-Ibáñez, M. Vergara, J.L. Sancho-Bru

In accordance with the regulations of the Universitat Jaume I, this thesis is published in its repository in open acces. For those papers with embargo period, the url to the original website of the Journal will be provided.

Chapter 1

First chapter tackle the revision of actual state of the assessment of the hand functionality. Functional assessment is a required practice, both in the disability appraisal and in rehabilitation. Both aspects are analyzed, showing the importance of ADL in functional assessment and the role that the hand plays in the performance of these ADL.

In this chapter it is evidenced that there is no objective functional evaluation methods of the hand valid for different patient populations. In addition, it has been shown that hand kinematics is of utmost importance for hand function and might be used to obtain objective functionality outcomes. The challenge raised by Coupier et al. (Coupier et al. 2016) of characterizing the hand function based on its kinematics despite the difficulty of hand kinematics recording is tackled in this thesis. Hence, the core of the thesis is the search of contributions to the functional assessment of the hand, focusing on its kinematics.

Chapter 2

Two important questions are addressed in this chapter. Which are the most relevant grasps for sufficiency? Are the most used grasps the most important ones for functionality?

A field study (1st experiment) was carried out, consisting on recording - videos to subjects with healthy hands while performing different ADL selected from the ICF. One hundred and forty-five videos were selected and visually analyzed to establish the grasp type that is being used at every instant. After appropriate weighting of time and importance of each activity for functionality, a rating of the relevancy of the different grasp types for functionality was obtained.

This information can be used to assess the hand functionality, and to strengthen the rehabilitation of the most important grasps to ensure an effective rehabilitation.

Chapter 3

Interrelation of maximum ranges of motion of MCP joints of adjacent fingers is addressed in this chapter. Both, mechanical and neural coupling lead to synergies underlying hand movements, which also affects joint angle limits (Lang & Schieber 2004). The interrelation between MCP joints was already observed in previous works (Santello et al. 1998), but was not quantified.

Consequently, an experiment (2nd experiment) was carried out in which the maximum achievable flexion/extension angles at the MCP joints of index, middle, ring and little fingers were measured while some of them were kept at specific angles. This was done by using a videogrammetric technique (see Appendix for sign convention) as MoCap system (Sancho-Bru et al. 2014). This experiment allowed identifying that maximum joint angles were significantly dependent on the posture of the rest of fingers. Also, equations for estimating the maximum joint angles depending on the rest of joint angles were provided.

These equations can be incorporated to existing biomechanical models, but can be used also to check differences between the existing interrelations in pathological hands and those in the healthy hand, which may affect the hand function. Also, during the development of this work a double hindrance was observed regarding the use of reflective markers: they interfered with the normal development of ADL, and many hiding problems were observed, which make its use unfeasible for the study of the hand kinematics during ADL.

Chapter 4

Given the problems of the videogrammetic technique of markers hiding and interference in ADL performance, the use of an instrumented glove was checked for the kinematic characterization of the hand during ADL. The instrumented glove turned out to be a cheap solution, easily portable, and even though the stiffness of the glove can slightly affect the angles achieved, this is a minor disadvantage when compared with the hiding problems from the videogrammetric technique.

Calibration protocols of the glove existing in literature are tedious and non-suitable for injured hands, or lack from accuracy (Buffi et al. 2014). A 3rd experiment was developed in order to obtain a feasible and reliable protocol. An across-subject calibration (see Appendix for sign convention), needing only recording one reference posture, was tested. Errors made with this protocol were in the same order of using an accurate subject-specific calibration.

The resulting protocol is a significant contribution for obtaining reliable kinematic data during ADL, even on patients, since just a simple reference position is required.

Chapter 5

Once the problem of measuring the kinematics of the hand in ADL was solved, a 4th experiment was implemented. Twenty-four right-handed subjects, free of hand pathologies, performed 24 ADL within the areas of Communicating, Mobility, Self-care and Domestic Life of the ICF. ADL were performed in laboratory conditions with real objects and guided indications. Kinematic data was recorded using the protocol presented in chapter 4 (see Appendix for sign convention). Hand postures recorded during the performance of ADL were used to calculate FROM of hand joints. The same protocol was used to record different static postures, representative of the AROM of the different hand joints.

Many directly usable data are provided: values of general and per activity FROM and the statistical distribution of the angles used during ADL, globally and per ICF area.

Furthermore, tables for the estimation of functional recovery based on AROM restored are provided.

Additionaly, a comparison between AROM and FROM is performed, in order to allow using AROM values in functional assessment. Furthermore, the AROM and FROM dependence on gender and hand size is investigated.

Chapter 6

The data obtained in the 4th experiment was also used in this chapter for a prospective study to check the feasibility of using PCA on the hand kinematics as a tool to assess the functionality of the hand.

PCA was applied to the 16 hand joint angles measured (24 subjects & 24 ADL), after appropriate weighting of the data so that each ADL weighted the same. The hand kinematics during ADL was proved to be low dimensional (5 factors accounted for 73.7% of the variance). Interpretation of these factors (synergies) was performed, and statistics of each of them and their temporal derivatives were computed. Also, statistics from additional measurements and tests currently used in clinical assessment were obtained.

Two patients carried out the same experiment, and comparison of their kinematics with that of the healthy hands was performed in terms of the similarity of the synergies and in terms of their relative use. The proposed methods were checked to be applicable to patient population, and turned out to provide easily interpretable data for hand function assessment.

OTHER PUBLICATIONS/CONGRESSES

Apart from the publications that integrate this thesis, I contributed in the development of other articles or congress communications related with the research presented in the thesis. They are presented in Table 0.4.

Table 0. 4. . Other publications where the autor took part

Other publications related where the author took part during the development of the thesis	
Journal Article	M.Vergara, J.L. Sancho-Bru, V. Gracia-Ibáñez, A. Pérez-González. (2014) **An introductory study of common grasps used by adults during performance of activities of daily living**. Journal of Hand Therapy 27 (2014), 225-234.
Congress	V. Gracia-Ibáñez, M. Vergara Monedero, J. L. Sancho-Bru (2014) **Evaluación de la función de la mano en actividades de la vida diaria**. XXVII Congreso Sociedad Ibérica de Biomecánica y Biomateriales Biomateriales.
Congress	Gracia-Ibáñez, V., Vergara, M., & Sancho-Bru, J. L. (2015) Importance of grasp types for personal autonomy during activities of daily living (ADL). 9th Triennial Hand and Wrist Biomechanics International (HWBI) Symposium Milan, Italy, June 16-17, 2015
Congress	V. Gracia-Ibáñez, M. Vergara, J. L. Sancho-Bru (2014) **Estudio de la flexo-extensión combinada de las articulaciones metacarpofalángicas**. XX Congreso Naciona de Ingeniería Mecánica.
Congress	M. Vergara, J. Sancho-Bru, V. Gracia-Ibañez (2015) **Estudios de caracterización cinemática de la mano sana en actividades de la vida diaria.** V Reunión del Capítulo Español de la Sociedad Europea de Biomecánica. Madrid
Congress	V. Gracia-Ibáñez, M. Vergara, J. L. Sancho-Bru (2016) **Human hand synergies in activities of daily living**. 22th Congress of the European Society of Biomechanics. Lyon, 2016.
Journal Article	N. Jarque-Bou, V. Gracia-Ibáñez, J.L Sancho-Bru, M. Vergara, A. Pérez-González, F.J. Andrés (2016). **Using kinematic reduction for studying grasping postures. An application to power and precision grasp of cylinders**. Applied Ergonomics, Vol. 56, 52-61.
Congress	Alba Roda Sales, Margarita Vergara, Joaquín L. Sancho-Bru, Verónica Gracia-Ibáñez (2016). **Quantifying the effect on hand posture when using adapted products for daily living activities.** 25nd Congress of the European Society of Movement Analysis for Adults and Children, Seville.
Congress	Margarita Vergara, F. Javier Andrés, Verónica Gracia-Ibáñez, Joaquín L. Sancho-Bru (2016). A study about the relationship between hand/arm anthropometry and grip/pinch strength. 22nd Congress of the European Society of Biomechanics, Lyon.

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Chapter
01

EVALUATION OF HAND FUNCTIONALITY DURING ACTIVITIES OF DAILY LIVING (ADL). A REVIEW

ABSTRACT, KEY TERMS & ABBREVIATIONS

Abstract

Over a billion people (about 15% of the world's population) are estimated to be living with some disability, according to the World Health Organization (WHO). To protect the human rights of people with disability, a great effort is being made to unify the classification of disabilities. The WHO's International Classification of Functioning, Disability and Health (ICF) has become a recognized reference for classifying the degree of disability. Beyond the obvious limitations derived from the lack of body functions and structures, the ability to carry out Activities of Daily Living (ADL) is proposed in the ICF as the main factor for classifying the degree of disability. According to the ICF, many of the deficiencies in the domains of activity and participation are focused on the upper limbs. Furthermore, hands are used for more than 5 hours a day only in ADL, excluding the time spent on working or sleeping. The functional evaluation of the hand in ADL is therefore essential to assess a person's degree of independence. Moreover, this evaluation is also important when it comes to examining the progress of rehabilitation programmes or in clinical practice. At present, the functional evaluation of the hand is performed using qualitative methods like "Disabilities of the Arm, Shoulder and Hand" (DASH), some of which are highly subjective and valid only for a specific pathology. Objective methods like measuring passive ranges of angles or maximal forces for specific types of grasps are also used, but no objective measurements while performing ADL are considered. No consensus has been reached about a unified method to assess hand functionality while performing ADL, as might be desirable, so that professionals have to rely on their own experience to grade this.

The aim of this chapter is to review the role of the use of the hand in the ability to perform ADL, with special attention given to the evaluations of functionality that are being used to establish the degree of disability and to monitor the evolution in rehabilitation processes for different pathologies of the hand. Special attention is paid to analysing the attempts that have been made to objectify the evaluation of hand disabilities through the analysis of grasp and handling, and their impact on current practice.

Key terms

Functionality of the hand, activities of daily living, disability, rehabilitation

Abbreviations

ADL: Activities of Daily Living
AMA: American Medical Association
CRPD: Convention on the Rights of Persons with Disabilities
DASH: Disabilities of the Arm, Shoulder and Hand

ICF: International Classification of Functioning, Disability and Health
UN: the United Nations
WHO: World Health Organization

1.1 Introduction

The human hand is one of the most complex and versatile mechanical systems. Its ability to grasp and manipulate is fundamental to be able to perform a great number of the activities of daily living (ADL) (Vergara et al. 2014). Therefore, keeping the functionality of the whole hand is critical to ensure a full and autonomous life, not only in ADL but also in work life (Bullock et al. 2013; Zheng, Rosa, et al. 2011). In fact, an impairment at the level of the metacarpophalangeal joints accounts for 54% of whole-person disabilities (Engelberg 1988).

Because of the importance of the hand for performing ADL, the International Classification of Functioning, Disability and Health (ICF) of the World Health Organization (WHO) (WHO 2001) established the ability to carry out ADL as the main factor for classifying the degree of disability. The WHO also emphasizes that the consequences of the disabilities depend to a large extent on the context: people with similar limitations, derived from the lack of body functions and structures, or with impairments that prevent them from performing ADL can experience a variety of difficulties in their lives, depending on their birthplace or place of residence.

Attempts have been made to universalize the protection of human rights for people with disability through the United Nations' (UN) Convention on the Rights of Persons with Disabilities (CRPD) (UnitedNations 2006) and, more recently, through the World Report on Disability (WHO 2011). However, this will be difficult to accomplish with the current procedures for establishing the degree of disability.

Nowadays, in the case of the hand, the functional assessment that is commonly used lacks objectivity. Focusing on the assessment of hand functionality, the tools used by the professionals are limited to goniometers for measuring passive ranges of motion (Ellis & Bruton 2002; Norkin & White 2009; Macionis 2013; Engstrand et al. 2011) and, in some cases, dynamometers for measuring maximal pinch and grip forces (Bohannon 2001; Bohannon et al. 2006; Mathiowetz et al. 1984; Roberts et al. 2011; Rantanen 1999). With regard to the capabilities to perform ADL, subjective observations of such abilities are performed for a given list of ADL.

Furthermore, the assessment of the ability to perform ADL is useful not only to rate disability, but it is also of utmost importance to improve rehabilitation processes and surgical planning. Comprehending the implications of selecting a rehabilitative practice or a surgical procedure in the improvement of the functionality of the hand would make it possible to select the best option for the patient taking into account his or her habits and needs. Currently, professionals combine medical techniques like electromyography, radiography or tomography with subjective tests like the "Disabilities of the Arm, Shoulder and Hand" (DASH) test (De Smet et al. 2007; Hudak et al. 2008). These are tools whose adequacy has not been demonstrated sufficiently in all cases (Changulani et al. 2008) and that have very low repeatability and a high level of subjectivity (Grao et al. 2006).

In this chapter a review of the role played by the hand in the ability to perform ADL is carried out. Special attention is paid to the evaluation of hand functionality in order to assess disability and to evaluate the progress achieved in rehabilitation processes or the restoration of hand functions after surgery.

1.2 ADL and disabilities

Beyond the humanitarian aspect, worldwide disability figures can give an idea of the magnitude of the problem and its impact on the global economy. As reported by the UN, there are approximately 650 million persons with disabilities in the world (about 10% of the global population, the WHO reports over a million), with approximately 80% of them living in developing countries, under conditions of poverty and with restricted access to employment ("Mainstreaming disability in the development agenda" 2008). A report from the Australian Network on Disability (Deloitte Access Economics 2011) estimated that "closing the gap between labour market participation rates and unemployment rates for people with and without disabilities by one-third would result in a cumulative $43 billion increase in Australia's gross domestic product over a decade in real dollar terms".[1]

Fortunately, the concept of disability, and the way people with disabilities are treated, has evolved a lot throughout history. The English Elizabethan Poor Laws (1598-1601) expelled them from hospitals and monastery shelters for the poor. They were given a cap to collect alms, which is the origin of the term "handicap" and the reason why this term is considered offensive nowadays. During World War II they were considered genetically defective and were "mercy killed". In the 40s the perception changed: they were considered unfortunate and the objects of charity. In 1970s' different movements driven by the efforts of disabled people to acquire new rights and entitlements came into being. The problem started to be located not in the individual but in the environment (attitudes and barriers, lack of services). Since then, the social perspective, guided by international institutions like the UN or WHO, has improved as a result of the efforts made to try to get them to become independent, self-determined individuals and to recognize their equal rights and opportunities. The ICF (World Health

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[1] These estimates only account for the direct impact on gross domestic product, and do not include indirect effects from improved government fiscal balances and increased employment opportunities for careers.

Organization 2002) substituted the concepts of "impairment", "disability" and "handicap" with those of "body functions and structures" and "activities-participation", highlighting the positive aspects (health) at the expense of the negative ones (weaknesses) and granting more importance to the socio-sanitary criteria to the detriment of those purely scientific ones (Hernandez-Milagro et al. 2008).

The meaning of having disabilities changes significantly depending on the person's place of birth. Developed countries, in general, have ratified and adhered to the CRPD. Policies in USA or Europe, although different, all guarantee minimum rights and promote integration. The specific actions carried out include training to promote societal integration, individual economic aids and social benefits, economic benefits to companies that favour the employment of people with disabilities, etc. And access to these aids depends on the degree of disability assessed by the relevant national agency. In countries that have ratified the CRPD and must therefore follow the precepts of the ICF, the criteria for assessing disability should be expected to be the same. Nevertheless, due to the lack of objective tools, the desired uniformity does not seem to have been achieved. This leads to a different way of assessing disability in each country, so that estimates of the number of people with disabilities vary greatly depending on who publishes them. Many low-income African countries, for example, report prevalence rates under 5%, while high-income countries report rates on average in excess of 10%, some as high as 20% (Loeb et al. 2008).

It is common to distinguish between assessment of work disability and assessment of disability. Work disability is a status of disease that prevents a person, either temporarily or permanently, from performing a professional activity. And disability, as defined by the WHO (World Health Organization 2002), is a general term for the functional impairment resulting from injury or disease that limits the normal performance of ADL, also taking into account environment and participation restrictions. Many countries, thus, usually have two different agencies to assess them, as well as different compensation programmes for each case. The assessment of work disability, as expected, does not usually consider the ability to perform ADL, but only the ability to perform work activities. In the case of Spain, where the authors reside, such assessment consists in a quantitative evaluation using the American Medical Association (AMA) Guides as a reference. These Guides offer a system for rating impairment by introducing some data about body functions and structures, although they are not universally accepted and, in fact, are based largely on consensus rather than on scientific evidence (Holmes 2013). In order to rate the disability and determine the associated economic benefits, Spain relies fully on the percentage of whole-person impairment published in the AMA Guides, as do many other states. With regard to the assessment of disability, the ICF established the ability to carry out ADL as the main factor for classifying the degree of disability. However, the countries that adhered to the ICF are applying it to their regulations with huge differences in both time and procedure. In the Spanish case, for example, the regulation that assesses disability came into force in 1999 and has still not been adapted to the ICF. Hence, the evaluation of disability does not take into account the limitations to perform ADL. On the contrary, it uses the degree of impairment of body structure, which is directly linked with a functional deficiency through the AMA Guides. In addition, in 2006, a new law came into force to introduce the concept of dependency: the functional inability to carry out ADL and thus requiring the care of a third person. This assessment is the first attempt made in Spain to consider the ability to perform ADL through the ICF of the WHO, and also provides for economic benefits, which complement the benefits stemming from the recognition of disability of the previous law.

1.3 ADL in rehabilitation or clinical evaluation

Assessing the ability to perform ADL is also important to be able to establish the level of improvement in rehabilitation processes and to choose the best clinical treatments for enhancing the capability to perform ADL and therefore gain autonomy and happiness. The rehabilitation might also be achieved in a shorter time, with substantial cost savings.

Many studies have examined the evolution of the ability to perform ADL in patients under clinical or rehabilitation treatments (Bendstrup et al. 1997; Chemerinski et al. 2001; Bartolo et al. 2012). Movement skills such as grasp and manipulation seem to be directly related with the capability to perform ADL. However, the capacity to perform ADL depends not only on physical capacities, but also on the performance of the cognitive function as well as on the person's participation or social skills. Knowledge of these relationships is of great importance in rehabilitation practice in order to guide interventions towards meaningful targets (Coster et al. 2007). In fact, rehabilitation processes seem to be more effective when ADL are trained directly, for example with the support of virtual reality technology (Lee et al. 2003; Guidali et al. 2011). Therefore, assessing the ability to perform ADL is a widely-used method in quantifying both physical and psychological damage. The paradigm of using this method is probably in cases of strokes and geriatric rehabilitation. For example, in strokes, the ability to perform ADL has long been considered a measure to assess their progress (Chiou & Burnett 1985; Hellström et al. 2003) and the rehabilitation exercises that are used are designed to improve ADL (Mehrholz et al. 2011). In the case of geriatric rehabilitation, different scales are used to verify the improvements in the ability to perform the ADL (Demers et al. 2010).

Furthermore, the assessment of the ability to perform ADL is used not only in general assessments but also to study specific pathologies or diseases. As an example, it has been used in assessing loss of vision in the elderly (Kempen et al. 2012), in assessing the improvements afforded by rehabilitation in older people with femoral neck fractures (Stenvall et al. 2007) or in other conditions such as chronic obstructive pulmonary disease (Bendstrup et al. 1997). Similarly, assessing the ability to perform ADL is not only used to evaluate the improvement in cases of physical illness, but is also widely used in cases of neurological disorders such as dementia (Mioshi et al. 2013; Liu et al. 2007; Littbrand et al. 2011) or Alzheimer (Marshall et al. 2011; Ávila et al. 2004).

In most studies the way of measuring the ability to perform ADL is often subjective, according to different scales (Stenvall et al. 2007; Hellström et al. 2003; Chiou & Burnett 1985). However, there are some cases where attempts have been made to use objective means of measuring the kinematic ability to carry out ADL. Henmi et al. (Henmi et al. 2006) used an optical three-dimensional motion analysis system when monitoring the kinematics of the neck and upper limbs while performing ADL. Hemmerich et al. (Hemmerich et al. 2006) measured the kinematics of the hip, knee and foot while performing ADL using a 6 degree-of-freedom electromagnetic tracking system. Similarly, Samuel et al. (Urwin et al. 2013) used an electrogoniometer to evaluate the kinematics of the knee while performing ADL. Electrogoniometry has also been used to study the effect of rigid cervical collar height on the full, active and functional range of motion during fifteen ADL (Miller et al. 2010).

1.4 The role of the hand in the ability to perform ADL

The analysis of specific grasps is a common practice in the biomechanical and rehabilitation fields (Sancho-Bru et al. 2003; Pérez-González et al. 2012; Podobnik et al. 2009; Connell et al. 2014). The selection of these grasps as being representative of hand behaviour is performed in many cases with a lack of scientific rigour (S L Kilbreath & Heard 2005); (Zheng, Rosa, et al. 2011) (Sollerman & Ejeskar 1995). In a previous study (Vergara et al. 2014), the authors performed a field study (on a representative sample of the adult population of a developed country) aimed at providing knowledge on the frequency and duration of use of the different types of grasp when performing different ADL. These data can be very useful in the assessment of the functional recovery of the hand during rehabilitation after injury or disease, for making clinical decisions and for prostheses design (Sollerman & Ejeskar 1995), among others. The ADL were classified into 8 areas (food preparation, feeding, personal care, housekeeping, shopping, driving and transport, leisure, and others that are difficult to classify like talking on the phone, moving around the house, etc.), in an attempt to represent the most common ADL carried out by adult people. These areas represent a total of 8.42 hours on average per day (according to the data reported by the American Time Use Survey) and more than 5 hours using hands (Vergara et al. 2014). Work time was not considered.

The results drawn from this study showed that the areas in which hands are used for more time are feeding and leisure and the most frequently used grasp, overall, is the pinch. However, though almost all grasps are used in all areas, they are used with different frequencies or durations; for example, the pinch is used to a great extent in areas like food preparation or leisure, but less in driving. It is remarkable that the most widely used grasps involve the thumb in opposition to the palmar side of the fingers (thumb in abduction), whereas the least used grasps either do not involve the thumb at all or the thumb is in opposition to the lateral side of the fingers. It is also significant that the amount of time in which both hands are used simultaneously is greater than when they are used alone, regardless of whether it is the right or the left hand. Grasps requiring more dexterity, like the pinch, are widely used by the right hand in the right-handed population, while other helping grasps, like non-prehensile grasp, are often used by the left hand to help the right hand.

In order to make these data more useful for disability assessment, it is very convenient to identify the activities of the ICF established by the WHO in which the hand is involved and which grasps are more frequently used in those activities. We have analyzed the activities of Part 1 "Functioning and Disability" of the ICF (Part 2 "Contextual Factor" refers to "Environmental and Personal Factors"). Part 1 is divided into two components: a) Body Functions and Structures, and b) Activities and Participation. Body functions are the physiological functions of body systems (including psychological functions), whereas Body structures are anatomical parts of the body such as organs, limbs and their components. In order to consider the role of the hand in the ability to perform ADL, only the second component, i.e. Activities and Participation, has been analyzed. Table 1.1 shows all the chapter headings for this component as well as the subdivisions (items) until the level of three-digit codes, according to the ICF classification. The following gradation was considered: "A" means that there is a direct and unpreventable involvement of the hand; "B" means that it is indirectly involved, and "C" means no involvement at all. As an example, "A" is selected for activities such as "Dressing" (d540) or "Eating" (d550), as hands are essential in these activities; "B" is used for "Learning to read" (d140), which involves hands indirectly to hold a book or pass the pages; and "C" is considered for Interpersonal relationships, as it is assumed that interacting socially does not necessarily involve contact or actions with the hands.

1.5 The present status of the assessment of functionality of the hand

Regardless of whether the evaluation of the functionality of the hand is required to assess disability or to assess rehabilitation processes and clinical treatments, the first step is always to identify the pathology or disease that causes the loss of functionality, which may be injuries specific to the hand or other diseases that can affect functionality indirectly. This is usually performed by medical professionals using clinical diagnostic tests (X-rays, Computed Tomography, Electromyography, etc.). This diagnosis should be carried out in accordance with the WHO's International Classification of Disabilities (WHO 2010), and allows the medical team to gain an idea of what kind of actions might be hindered by the pathology, which can be helpful in order to assess the level of functionality of the hand. However, at this point the need for tools and methodologies capable of taking into account the subject's particularities arises. These tools should ideally be valid for any disease or pathology affecting the hands, and should be able to assess the subject's loss of hand functionality both objectively and accurately.

Table 1.1. Level of involvement of the hand in "Activities and Participation" of the ICF

TABLE 1.1	**LEVEL**		
ACTIVITIES AND PARTICIPATION	A	B	C
Chapter 1 Learning and applying knowledge			
Purposeful sensory experiences			
d110 Watching			■
d115 Listening			■
d120 Other purposeful sensing		■	
d129 Purposeful sensory experiences, other specified and unspecified		■	
Basic learning			
d130 Copying		■	
d135 Rehearsing		■	
d140 Learning to read		■	
d145 Learning to write		■	
d150 Learning to calculate		■	
d155 Acquiring skills		■	
d159 Basic learning, other specified and unspecified		■	
Applying knowledge			
d160 Focusing attention			■
d163 Thinking			■
d166 Reading		■	
d170 Writing		■	
d172 Calculating		■	
d175 Solving problems			■
d177 Making decisions			■
d179 Applying knowledge, other specified and unspecified			■
d198 Learning and applying knowledge, other specified			■
d199 Learning and applying knowledge, unspecified			■
Chapter 2 General tasks and demands			
d210 Undertaking a single task		■	
d220 Undertaking multiple tasks		■	
d230 Carrying out daily routine		■	
d240 Handling stress and other psychological demands			■
d298 General tasks and demands, other specified		■	
d299 General tasks and demands, unspecified		■	
Chapter 3 Communication			
Communicating - receiving			
d310 Communicating with - receiving - spoken messages			■
d315 Communicating with - receiving - nonverbal messages			■
d320 Comm. with - receiving - formal sign language messages			■
d325 Communicating with - receiving - written messages		■	
d329 Communicating - receiving, other specified and unspecified			■
Communicating - producing			
d330 Speaking			■
d335 Producing nonverbal messages	■		
d340 Producing messages in formal sign language	■		
d345 Writing messages	■		
d349 Communication - producing, other specified and unspecified	■		
Conversation and use of communication devices and techniques			
d350 Conversation			■
d355 Discussion			■
d360 Using communication devices and techniques	■		
d369 Conversation and use of comm. devices and tech., other specified and unspecified		■	
d398 Communication, other specified		■	
d399 Communication, unspecified		■	

TABLE 1.1 (cont.)	**LEVEL**		
ACTIVITIES AND PARTICIPATION	A	B	C
Chapter 4 Mobility			
Changing and maintaining body position			
d410 Changing basic body position		▨	
d415 Maintaining a body position			░
d420 Transferring oneself		▨	
d429 Changing and maintaining body position, other specified and unspecified		▨	
Carrying, moving and handling objects			
d430 Lifting and carrying objects	■		
d435 Moving objects with lower extremities	■		
d440 Fine hand use	■		
d445 Hand and arm use	■		
d449 Carrying, moving and handling objects, other specified and unspecified	■		
Walking and moving			
d450 Walking			░
d455 Moving around		▨	
d460 Moving around in different locations			░
d465 Moving around using equipment		▨	
d469 Walking and moving, other specified and unspecified		▨	
Moving around using transportation			
d470 Using transportation		▨	
d475 Driving	■		
d480 Riding animals for transportation	■		
d489 Moving around using transportation, other specified and unspecified		▨	
d498 Mobility, other specified		▨	
d499 Mobility, unspecified		▨	
Chapter 5 Self-care			
d510 Washing oneself	■		
d520 Caring for body parts	■		
d530 Toileting	■		
d540 Dressing	■		
d550 Eating	■		
d560 Drinking	■		
d570 Looking after one's health		▨	
d598 Self-care, other specified	■		
d599 Self-care, unspecified	■		
Chapter 6 Domestic life			
Acquisition of necessities			
d610 Acquiring a place to live		▨	
d620 Acquisition of goods and services		▨	
d629 Acquisition of necessities, other specified and unspecified		▨	
Household tasks			
d630 Preparing meals	■		
d640 Doing housework	■		
d649 Household tasks, other specified and unspecified	■		
Caring for household objects and assisting others			
d650 Caring for household objects	■		
d660 Assisting others	■		
d669 Caring for household objects and assisting others, other specified and unspecified	■		
d698 Domestic life, other specified		▨	
d699 Domestic life, unspecified		▨	

TABLE 1.1 (cont.)	**LEVEL**		
ACTIVITIES AND PARTICIPATION	A	B	C
Chapter 7 Interpersonal interactions and relationships			
General interpersonal interactions			
d710 Basic interpersonal interactions			░
d770 Intimate relationships (include sexual relationships)		▒	
d729 General interp. interactions, other specified and unspecified			░
Particular interpersonal relationships			
d730 Relating with strangers			░
d740 Formal relationships			░
d750 Informal social relationships			░
d760 Family relationships			░
d770 Intimate relationships			░
d779 Particular interpersonal relationships, other specified and unspecified			░
d798 Interp. interactions and relationships, other specified			░
d799 Interpersonal interactions and relationships, unspecified			░
Chapter 8 Major life areas			
Education			
d810 Informal education		▒	
d815 Preschool education		▒	
d820 School education		▒	
d825 Vocational training		▒	
d830 Higher education		▒	
d839 Education, other specified and unspecified		▒	
Work and employment			
d840 Apprenticeship (work preparation)		▒	
d845 Acquiring, keeping and terminating a job		▒	
d850 Remunerative employment		▒	
d855 Non-remunerative employment		▒	
d859 Work and employment, other specified and unspecified		▒	
Economic life			
d860 Basic economic transactions		▒	
d865 Complex economic transactions		▒	
d870 Economic self-sufficiency		▒	
d879 Economic life, other specified and unspecified		▒	
d898 Major life areas, other specified		▒	
d899 Major life areas, unspecified		▒	
Chapter 9 Community, social and civic life			
d910 Community life		▒	
d920 Recreation and leisure	▓		
d930 Religion and spirituality		▒	
d940 Human rights		▒	
d950 Political life and citizenship		▒	
d998 Community, social and civic life, other specified		▒	
d999 Community, social and civic life, unspecified		▒	

As regards the assessment of disability, the WHO's ICF (WHO 2001) requires taking into account both the "Functioning and Disability" and the "Contextual Factors". As said before, the first component includes both the "Body Functions and Structures", i.e. structural and functional impairment, and "Activities and Participation", i.e. the ability to perform ADL. The methods currently used to assess the "Body Functions and Structures" for the case of the hand are limited to measuring passive ranges of motion with goniometry (Ellis & Bruton 2002; Norkin & White 2009; Macionis 2013; Engstrand et al. 2011) or maximal forces in cylindrical and pinch grasps with dynamometers (Bohannon 2001; Bohannon et al. 2006; Mathiowetz et al. 1984; Roberts et al. 2011; Rantanen 1999). The "Activity and Participation" assessment is limited to the observation of specific actions that are intended to be representative of ADL, and questionnaires administered to the patients regarding their skills when performing ADL (Marshall et al. 2007; Jefatura del Estado España 2006). The assessment of hand functionality during rehabilitation processes or clinical planning is usually performed through highly subjective specific tests or scales for each pathology (Brogardh et al. 2007; Backman & Mackie 1995; Amirjani et al. 2011), combined with the objective measurement of passive ranges of motion using goniometers, and maximal cylindrical or pinch grasping forces using dynamometers.

With regard to the use of goniometry, institutions that have to assess disability have a latent problem because measurements are highly dependent on the operator's intention. In the measurement of the passive range of motion, an orthopaedic surgeon can force a joint more than a physical therapist or an assessment professional because of their professional experience and depending on what he expects to obtain (de Carvalho et al. 2012). There is an interest to link objective measurements of "normality" with the ability to perform ADL (Mary C. Hume et al. 1990; Faria-Fortini et al. 2011). Functional evaluators welcome any objective tool allowing them to do so, even when it is very simple (Soler & Rizos 2006). This is the case of a protocol that is widely used in Spain that consists in using a dynamometer to record the maximum force of the cylinder grasp and distal and lateral pinch and to estimate fatigue from a series of forces and times. It is also common practice to compare ranges of motion and maximal grasping forces of the healthy and affected hands of a subject or with respect to values taken from normality databases (Cano-de la Cuerda et al. 2008; Lorenzo-Agudo et al. 2007).

Some previous studies have reviewed the tests and scales used in clinical or rehabilitation practice (Metcalf et al. 2007); identified twenty-five different methods for conducting the clinical assessment of the upper limbs within the framework of the WHO's ICF. Thus, there are many tests available and medical professionals have to choose the most suitable for evaluating a specific pathology or illness, based on studies conducted to evaluate the sensitivity and validity for that specific pathology. For example, Lin et al. (Lin et al. 2010) analyzed the responsiveness and validity of three dexterous function measurements in stroke rehabilitation. Lemmens et al. (Lemmens et al. 2012) systematically reviewed the instruments used for assessing arm-hand skilled performance in patients with stroke or cerebral palsy. The instruments identified were mainly tests and scales, only applicable in most cases to stroke or cerebral palsy. Although many instruments exist to assess capacity and perceived performance, a lack of instruments for assessing actual performance was reported. Lemmens also evidenced a dearth of instruments intended to be applied simultaneously in both components of the ICF, "Body Functions and Structures" and "Activities and Participation".

Table 1.2 shows a description of 15 of the several tests and scales used in clinical and rehabilitation assessment. Actual assessments range from questionnaires with no objective data measured, such as the DASH (Figure 1.1) or Quality of Upper Extremity

Skills tests, to questionnaires where body functions are tested using data that are objective but were not obtained during the performance of ADL, such as the Purdue Pegboard or Nine Hole Peg tests (Figure 1.2).

Table 1.2. Review of assessments used for the functionality of the upper limb.

TABLE 1.2

Name of the assessment	Description	For specific diseases	Valid/ Specific for hand
Action Research Arm Test	Assesses upper limb functioning using observation. It is a 19-item measure (grasps and gross arm movement).	☐	☐
Arthritis Hand Function Test	Assesses hand strength and dexterity in patients with arthritis.	☐	☐
Box and Block Test	Assesses unilateral gross manual dexterity in cases of Stroke, Multiple sclerosis, Neuromuscular disorders, etc.	☐	☐
Conchin Hand Function Scale	Assesses functional ability of the hand in patients with arthritis, sclerosis, etc. 18-item questionnaire.	☐	☐
DASH	Assesses the loss of functionality in patients with upper limb disorders. 30-item questionnaire about ADL.	☐	☐
Frenchay Activities Index	Assesses a broad range of activities of daily living in patients recovering from stroke.	☐	
Fugl-Meyer Test	Assesses motor recovery after stroke. 226 items across 5 domains.	☐	☐
Jebsen Test	Assesses a broad range of uni-manual hand functions required in ADL. 7-10 items timed.		☐
Michigan Hand Questionnaire	Assesses patient’s perception of hand function, pain and satisfaction on ADL. 37 items.		☐
Nine Hole Peg Text	Measures finger dexterity by taking pegs and placing them into holes following the instructions.	☐	☐
Purdue Pegboard Test	Assesses the dexterity of the hand, gross movements and fine “fingerprint” dexterity, in patients with Parkinson’s disease.	☐	☐
Quality of Upper Extremity Skills Test	Assesses movement patterns and hand function in children with cerebral palsy from ages 18 months to 8 years.	☐	☐
Sollerman Test	Assesses hand function while performing ADL in Spinal Cord Injury patients. Scores timed range from 0-80.	☐	☐
Strength-Dexterity Test	Assesses the dynamic pinch performance used in ADL by testing strength and dexterity in some actions.		☐
Worf Motor Function Test	Assesses upper extremity motor ability through timed and functional tasks. It consists of 17-21 items.	☐	☐

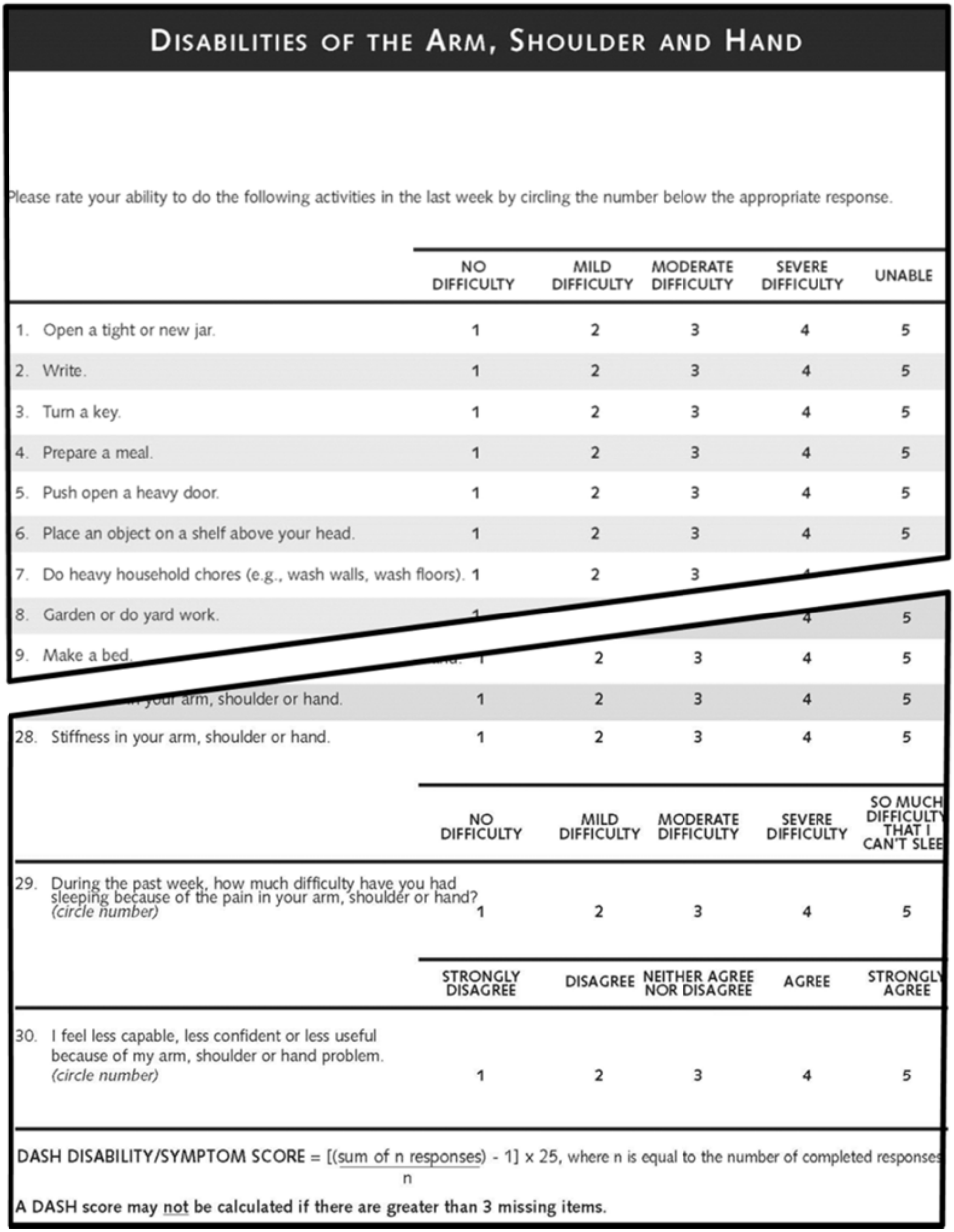
TABLE 1.2 (cont)

	ICF domain:			Type of data			
Name of the assessment	Body Functions and Structures	Activities and Participation	ADL capabilities directly inferred from the outcomes	Use of instrumentation	Objective data	Observation	Studies of reliability
Action Research Arm Test	☐*	☐	☐	☐		☐	☐
Arthritis Hand Function Test	☐	☐*		☐$	☐		☐
Box and Block Test	☐*	☐		☐	☐		☐
Conchin Hand Function Scale		☐	☐			☐	☐
DASH		☐	☐			☐	☐
Frenchay Activities Index		☐	☐			☐	☐
Fugl-Meyer Test	☐					☐	☐
Jebsen Test		☐	☐	☐$	☐	☐	☐
Michigan Hand Questionnaire		☐	☐			☐	☐
Nine Hole Peg Text	☐			☐	☐		☐
Purdue Pegboard Test	☐			☐	☐		☐
Quality of Upper Extremity Skills Test	☐					☐	☐
Sollerman Test		☐	☐	☐$	☐	☐	☐
Strength-Dexterity Test	☐	☐	☐	☐	☐		☐
Worf Motor Function Test	☐*	☐	☐	☐$		☐	☐

☐$ means that instrumentation is required, but common things can be used and it is free

☐* means that the level of assessing this domain is relative

Figure 1.1. Items of the DASH Questionnaire. Figure extracted from the Institute for Work & Health website (http://dash.iwh.on.ca/home). The questionnaire was developed by them, jointly with the American Academy of Orthopaedic Surgeons (AAOS).



DISABILITIES OF THE ARM, SHOULDER AND HAND

Please rate your ability to do the following activities in the last week by circling the number below the appropriate response.

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. Open a tight or new jar.	1	2	3	4	5
2. Write.	1	2	3	4	5
3. Turn a key.	1	2	3	4	5
4. Prepare a meal.	1	2	3	4	5
5. Push open a heavy door.	1	2	3	4	5
6. Place an object on a shelf above your head.	1	2	3	4	5
7. Do heavy household chores (e.g., wash walls, wash floors).	1	2	3		
8. Garden or do yard work.	1			4	5
9. Make a bed.	1	2	3	4	5
arm, shoulder or hand.	1	2	3	4	5
28. Stiffness in your arm, shoulder or hand.	1	2	3	4	5

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	SO MUCH DIFFICULTY THAT I CAN'T SLEE
29. During the past week, how much difficulty have you had sleeping because of the pain in your arm, shoulder or hand? *(circle number)*	1	2	3	4	5

	STRONGLY DISAGREE	DISAGREE	NEITHER AGREE NOR DISAGREE	AGREE	STRONGLY AGREE
30. I feel less capable, less confident or less useful because of my arm, shoulder or hand problem. *(circle number)*	1	2	3	4	5

DASH DISABILITY/SYMPTOM SCORE = $\left[\left(\frac{\text{sum of n responses}}{n}\right) - 1\right] \times 25$, where n is equal to the number of completed responses

A DASH score may not be calculated if there are greater than 3 missing items.

Figure 1.2. Images of instrumentation used in different assessment scales or tests.

Action Research Arm Test

Box and Block Test

Nine Hole Peg Test

Purdue Pegboard Test

Only some of the tests presented evaluate the ability to perform ADL through observation, such as the Sollerman or Jebsen tests. Furthermore, there are very few experimental studies dealing with the objective assessment of the intact upper limb function while performing ADL (Chen et al. 2010; van Andel et al. 2008; Aizawa et al. 2010; Sheikhzadeh et al. 2008; Butler et al. 2010; Alt Murphy et al. 2006; Magermans et al. 2005), and even fewer that refer specifically to the hand (Rahman et al. 2013; Luker et al. 2014; Oess et al. 2012). And there are also few studies assessing the pathological upper limb (Molina Rueda et al. 2012; Murgia et al. 2010) or hand (Wade et al. 2014) functionality while performing ADL. Moreover, these studies are biased to a particular disease or to a specific activity. For example, Murgia et al. (Murgia et al. 2010) studied the use of a kinematic indicator to assess the upper extremity status of distal radius fracture patients, but they only considered the activity of page-turning. And Molina et al. (Molina Rueda et al. 2012) registered the kinematics and electromyography of the upper limb of patients with upper extremity hemiparesis due to stroke, during the activity of drinking from a glass.

1.6 Conclusion

The objective assessment of hand functionality while performing ADL, from experimental data registered in healthy and pathological hands, is a field that still requires a great deal of work. Given the importance of assessing the functionality of the hand, both in the field of disability evaluation and in rehabilitation and clinical practice, and taking into account the analysis of the present status, two matters become obvious:

Firstly, the analysis of hand functionality is very important in the context of the performance of ADL, particularly within the framework of the WHO's ICF. As more countries ratify the UN Convention, there is an increasing interest to improve disability assessment in order to follow the precepts of the WHO. Recent literature also reveals a growing interest to evaluate the patient's progression during rehabilitation processes for specific diseases based on the evolution of the ability to perform ADL. The development of a tool to assess the functionality of the hand during the different ADL required for the patient's autonomy and valid for any disease would be highly desirable.

Secondly, actual procedures to assess hand functionality while performing ADL present a lack of objectivity that makes it difficult to infer the patient's progress in the ability to carry out ADL. Moreover, the tests or scales available today are only applicable for specific diseases. The conclusion is that there is a need for a general and objective tool to assess the functionality of the hand.

New tools for functional assessment are called for, and especially scales than can be applied simultaneously in both components of the ICF: "Body Functions and Structures" and "Activities and Participation". Such a tool could link the two components (the lack of functionality in performing ADL due to the occurrence of a structural impairment) and would simplify the assessments, thus making them more realistic (the maximum range of motion is not always required to perform ADL).

Finally, although the ability to grasp and handle is essential to be able to perform ADL, not many attempts have been made to objectify the evaluation of hand disabilities through the analysis of grasp and handling. It is true that there are some studies in the field of rehabilitation that use grasp capabilities to improve the ability to perform ADL, mainly in stroke patients. However, the use of grasps in ADL has seldom been linked as a way to measure and assess the functionality of the hand.

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Chapter
02

RELEVANCE OF GRASP TYPES TO ASSESS FUNCTIONALITY FOR PERSONAL AUTONOMY

ABSTRACT, KEY TERMS & ABBREVIATIONS

Abstract

Study Design: Cross-sectional research design.

Introduction: Current assessment of hand function is not focused on evaluating the real abilities required for autonomy.

Purpose of the Study: To quantify the relevance of grasp types for autonomy in order to guide hand recovery and its assessment.

Methods: Representative tasks of the ICF-activities in which the hands are directly involved were recorded. The videos were analysed to identify the grasps used with each hand, and their relevance for autonomy was determined weighting time with the frequency of appearance of each activity in disability and dependency scales. Relevance is provided, globally and distinguishing by hand (right-left) and bimanual function. Significant differences in relevance are also checked.

Results: The most relevant grasps are pad to pad pinch, cylindrical, lumbrical, and special pinch together with the non-prehensile use of the hand. Relevance of the grasps is different depending on the hand and on bimanual function.

Discussion: Different relative importance was obtained when considering dependency versus disability scales. Pad to pad pinch and non-prehensile grasp are the most relevant for both hands, while lumbrical grasp is more relevant for the left hand and cylindrical grasp for the right one. The most significant difference in bimanual function refers to pad to pad pinch (more relevant for unimanual actions of the left hand and bimanual actions of the right).

Conclusions: The relative importance of each grasp type for autonomy and the differences observed between hand and bimanual action should be used in medical and physical decision-making.

Level of Evidence: N/A.

Key terms

Grasp taxonomy, ICF, daily life activities, right and left hand, simultaneous use of hands

Abbreviations

3FC-ICF-activities: activities classified within the ICF with a 3-figure code

ADL:	Activities of daily living
AROM:	Active range of motion
EGA:	Elementary grasp action
ICF:	International Classification of Functioning, Disability and Health

WCoeff_ScDi: Weighting coefficient obtained from disability scales
WCoeff_SvDe: Weighting coefficient obtained from dependency scales
WHO: World Health Organization

2.1 Introduction

Performance of activities of daily living (ADL) is critical to ensure a full and autonomous life (Vergara et al. 2015). Most movements in ADL require object manipulation with a stable handgrip (Lee & Jung 2015). Therefore, a decrease in the grasp capabilities arising from pathologies of the hands can generate a loss of functionality. In the occupational field, hand disorders are an important issue as they represent one third of all injuries at work (Marty et al. 1983). As a consequence, the study of the ability to grasp has been a permanent concern in biomechanics (Sancho-Bru et al. 2012; Buchholz & Armstrong 1992; Mora et al. 2012; Leon et al. 2012) and rehabilitation (Podobnik et al. 2009; de Castro & Cliquet Júnior 2000; Jones & Lederman 2006).

However, current assessment of hand function in clinical practice lacks a deep evaluation of the grasp ability. Some assessment methods are based in tests or scales that are usually validated for specific pathologies (Amirjani et al. 2011; Backman & Mackie 1995; Brogardh et al. 2007). They are usually highly subjective (De Los Reyes-Guzmán et al. 2014), including sometimes self-rated scales. Other more general methods are based on objective data such as active ranges of motion, tactile sensing or grasp strength, although these methods are still under research (Hume et al. 1990; Bain et al. 2014; Hayashi & Shimizu 2013; Lawrence et al. 2015; Boissy et al. 1999; Jones & Lederman 2006). Few methods evaluate the performance of some types of grasps, but they do not consider their relative importance for developing normal life (Brogardh et al. 2007; Light et al. 2002).

The International Classification of Functioning, Disability and Health (ICF) of the World Health Organization (WHO) was developed as a framework for evaluation (Lindner et al. 2010). The ICF provides a standard language and a common framework to compare by using a common metric: the impact on the functioning of the individual. The ICF considers positive functioning as the situation where the body is functional and with structural integrity, thus allowing the normal performance of activities and participation. The ICF develops these activities in its part ***d. Activities and Participation.*** The terms disability and dependency are highly related and often used interchangeably in the literature (Querejeta González 2004). Some works (Bjornestad et al. 2016) point out the lack of international consensus on the definition of concepts such as disability, functioning, autonomy, sufficiency or dependency. According to the ICF (World Health Organization 2002), functioning and disability are related domains of a single health construct. Functionality, as opposed to disability, is the capability to perform a specific activity. Some authors (Bjornestad et al. 2016) propose that autonomy (equivalent to sufficiency) and dependency are part also of another single construct. In this construct, dependency can be defined as a loss of autonomy and the need of support by a third person for ADL, especially self-care. A high grade of disability leads inevitably to dependency, but disability can exist without dependency. Full autonomy or sufficiency is reached when a person can develop a complete functional life in terms of performing all the necessary ADL for total functionality. In this sense, personal habits, roles and responsibilities of one person may influence the perception of autonomy of an individual. However, the scales used to rate both disability and dependency are common and general.

In fact, there are two issues to be considered when rating disability or dependency by assessing the capability to perform ADL: the selection of ADL and the relevance of the selected activities for autonomy. There is no consensus in which ADL must be considered for autonomy (Light et al. 2002; Magermans et al. 2005; Lemmens et al. 2012). In fact, the scales often consider for autonomy only some basic activities such as those of self-care, so that a person might be assessed as autonomous although he/she requires assistance to carry out activities such as cooking, shopping or going outside. All ICF-activities should be considered when using the ICF to assess autonomy, and a key question is establishing the importance of each activity for personal autonomy. In this regard, a worth mentioning study by Querejeta (Querejeta González 2004) collects a review of ratings applied by several European countries and organizations, summarized in two ratings that will be used in this work. The first rating measures the importance of each ICF-activity for disability, computed from the frequency of appearance (appearance coefficient, in %) of each ICF-activity in 23 scales used to globally rate disability, as Barthel Index, Functional Independence Measure or Katz Index. The second rating takes into account the importance of the activities for dependency, estimated through the frequency of appearance of the activities in several sociological surveys of public health in Spain. Both scales are not equivalent: the scales of disability give more importance than the surveys of dependency to transferring oneself or speaking, and less importance to household tasks (preparing meals, doing housework), the acquisition of goods and services, moving around and using transportation or recreation and leisure. Obviously, this dependency rating of the ICF activities has to be seen as a general rating, which may differ somewhat from particular individual's perceptions, affected by the personal habits, roles and responsibilities.

Knowledge of the daily frequency of usage of the different grasp types, along with time of hands working in unimanual or bimanual tasks, has been emphasized as essential to establish rehabilitation strategies (Vergara et al. 2014; Sharon L. Kilbreath & Heard 2005). Daily frequencies of different grasp types while performing ADL were provided in a previous work by the authors (Vergara et al. 2014). Nevertheless, that work was not focused on assessing disability but on daily time of use. The most commonly used grasps throughout the day are not necessarily the most important ones for autonomy; at least there is no evidence of it to date. Knowledge of the most needed grasps for autonomy would be a valuable reference in decision-making for medical and physical rehabilitation to reinforce the capacity to perform these grasps. In fact, 97.5% of therapists feel that

ADL-based strategies are important in hand therapy practice (Powell & von der Heyde 2014). However, assessing the capability to perform different grasp types is not a common practice to assess functionality. Light et al. (Light et al. 2002) attempted to assess functionality through the capability to perform different grasp types by assigning a unique grasp type to each activity, although different grasp types are usually required to complete a given ADL. They used a limited set of ADL as representative of the grasp types most commonly used, but they didn't weight the activities for autonomy. No previous work has attempted to establish the relevance of the different grasp types for assessing functional recovery or disability.

The objective of this work is to present the relevance of the different grasp types for disability assessment, within the framework of the ICF. A field study has been performed on healthy subjects to identify the grasps used during normal hand function by means of a thorough analysis of videos recorded while performing a set of activities selected according to the ICF. The importance of each grasp for autonomy is estimated using weighting coefficients obtained from the work of Querejeta (Querejeta González 2004).

2.2 Material and methods

The experiment was approved by the Ethical Committee of the University. Thirty-two right-handed subjects (16 males and 16 females) participated in the experiment (age 32.4 ± 12.5 years, hand length 180 ± 13 mm and hand breadth 81 ± 9 mm). All the participants were free of pathological conditions.

First, a set of ICF-activities in which the hands are directly involved was selected. Then, representative tasks accounting for each of these ICF-activities were recorded on video. The videos were subsequently analysed to identify the different grasps being used, and finally the importance of each grasp type for autonomy was determined.

2.2.1 Selection and recording of tasks

From the ICF part ***d. Activities and Participation***, the activities of the 3rd level (Subclass of the ICF up to a 3rd level, coded as d followed by 3 figures) were used in this study (Table 2.1), named as 3-figure code ICF-activities (3FC-ICF-activities), although we have looked into the activities of the 4th level, (Subclass of the ICF up to a 4rd level) if they existed, in order to select the representative tasks.

ICF chapters where the hands are not involved were not considered and neither were those referring to cognitive activities (how to learn, how to manage relationships, etc.). In all, chapters 3 (Communication), 4 (Mobility), 5 (Self-care), 6 (Domestic life) and 9 (Community, social and civic life) were considered. Within these chapters, 23 3FC-ICF-activities in which the hands are directly involved for grasping were identified by the authors. Some 3FC-ICF-activities were not considered, such as *d340 Producing messages in formal sign language*, as no grasp is required; *d480 Riding animals for transportation*, because it is only used in developing countries; and *d420 Transferring oneself*, as it requires the use of the hands simply as a fulcrum. Then, a total of 128 representative tasks of these 3FC-ICF-activities were selected and recorded on video (Figure 2.1). Each subject performed a reduced set of the tasks, and each task was performed by several subjects. When different ways of performing a given task (in terms of types of grasps) were found, more than one video was analyzed per task, so that 145 videos were finally thoroughly analysed as being representative of the 128 tasks.

Table 2.1. Chapters of the ICF

CHAPTERS OF THE ICF		
d1	Chapter 1	LEARNING AND APPLYING KNOWLEDGE
d2	Chapter 2	GENERAL TASKS AND DEMANDS
d3	Chapter 3	COMMUNICATION
d4	Chapter 4	MOBILITY
d5	Chapter 5	SELF-CARE
d6	Chapter 6	DOMESTIC LIFE
d7	Chapter 7	INTERPERSONAL INTERACTIONS AND RELATIONSHIPS
d8	Chapter 8	MAJOR LIFE AREAS
d9	Chapter 9	COMMUNITY, SOCIAL AND CIVIC LIFE

2.2.2 Analysis of the tasks recorded

First, each task was divided into consecutive elementary grasp actions (EGA) for each hand, considered as any complete action in which the hand performed a particular action using a fairly constant hand posture. Close to 2300 EGAs were analysed to identify the hand involved (right or left), the type of grasp used from a 9-type classification27 (Figure 2.2), the total time spent in the EGA and whether at any time during the EGA the task is bimanual or not. The nine types of grasps considered were enough to represent the grasping postures used for most of the EGA (97%) and included both power and precision grasps, as well as a non-prehensile grasp (objects are manipulated without being grasped).

Figure 2.1. All the 3FC-ICF-activities considered involving the hands and all the tasks recorded within each of them (there are 128 tasks from 23 different 3FC-ICF-activities).

TASKS RECORDED								
d3	COMMUNICATION		d4	MOBILITY		d6	DOMESTIC LIFE	
	d325	Reading a book or a journal		d410	Sitting in a dining chair		d620	Shopping items into boot
		Reading using a tablet			Sitting in an armchair			Handling trolley
	d335	Drawing			Standing up from a chair			Shopping: taking items
		Painting			Standing up from an armchair			Shopping: releasing items
		Taking photos		d430	Lifting objects			Shopping:paying
		Copying using a photocopier			Carrying objects in the hands			Shopping (vending machine)
	d345	Writting			Carrying backpack		d630	Cutting tomatoes
	d360	Talking using a telephone			Releasing objects			Peeling oranges (hand)
		Talking using a mobile		d440	Picking up toys			Peeling potatoes (knife)
		Using a smartphone			Picking up DVDs and CDs			Toasting a sandwich
		Using the tablet			Grasping and manipulating keys			Preparing sandwich
		Typing			Opening-closing locker (key)			Making salad
		Using the mouse of the PC			Introducing code in a device			Serving cake
d5	SELF-CARE				Handling bills and coins			Preparing & frying fish
	d510	Washing hands			Manipulating toys (Assembling)		d640	Clothes (washing machine)
		Taking a shower		d445	Pulling drawer			Taking out clothes (w/machine)
		Drying oneself			Pushing drawer			Washing dishes
	d520	Making up			Reaching sth from a shelf			Clearing the table
		Cream on hands			Throwing a ball			Sweeping
		Brushing teeth			Catching a ball			Ironing
		Combing			Opening/closing door (key)			Storing shopping items
		Nail polishing			Opening/closing door (handle)			Trash a paper
		Cutting toenails			Opening/closing emergency door			Folding clothes
	d530	Urinating			Opening/closing the boot			Placing wood (chimney)
		Defecating		d470	Lift		d650	Sewing
		Chanching sanitary napkin			Bus: Get a ticket			Cleaning furniture
		Chanching a tampon			Bus:Using transportation			Changing a lightbulb
	d540	Putting on a belt		d475	Driving a baby buggy			Plugging in appliances (PC)
		Putting on socks and shoes			Driving a wheelchair			Plugging in a toaster
		Taking off a shirt			Driving a car			Unplugging
		Taking off a jacket			Driving a car:Shift into gear			Changing batteries
		Taking off boots	d9	COMMUNITY, SOCIAL & CIVIC LIFE				Checking the oil
		Taking of shoes		d920	Playing cards			Pumping a tyre
		Hanging up clothes			Playing video-games			Folding a baby buggy
	d550	Eating a piece of toast			Playing chess			Folding a wheelchair
		Eating snacks			Playing dice			Taking care of plants
		Handling crockery & cutlery			Cutting with scissors			Taking care of animals
		Eating with a knife			Folding paper		d660	Washing a baby's hands
		Eating with a spoon			Gluing			Dressing a child
	d560	Opening a can			Channel hopping			Assisting child to move
		Opening a bottle tap			Playing DVD			Feeding a baby
		Drinking from a bottle						
		Drinking from a can						
		Serving and drinking water						
	d570	Healing a wound (Band-Aid)						
		Putting on and off glasses						
		Cleaning glasses						
		Blow your nose						

Figure 2.2. Examples of the grasp in the taxonomy. Cylindrical grasp (Cyl), Oblique palmar grasp (Obl), Hook (Hook), Lumbrical grasp (Lum), Intermediate power-precision grasp (IntPP), (Pad to pad Pinch PpPinch), Lateral Pinch (LatP), Special Pinch (SpP), Non prehensile grasp (NonP).

2.2.3 Analysis of data

As the durations of the videos for each task were very different, the time recorded for each EGA was weighted in order to equal the time of all the tasks within each 3FC-ICF-activity, and afterwards to equal the time of all the 23 3FC-ICF-activities recorded.

In order to consider the importance of each grasp type for disability and dependency, two additional weighting coefficients were used from the appearance coefficients by Querejeta (Querejeta González 2004) (Table 2.2): one of them rating the importance of the activity in scales of disability, Wcoeff_ScDi, and the other rating the importance of the activity in surveys of dependency, WCoeff_SvDe. In order to calculate the weighting coefficients for each of the 3FC-ICF-activities, the appearance coefficients have been scaled to one-hundred basis points. For those activities not considered in the work of Querejeta, the coefficient of the most similar activity was used (e.g. for *d345 Writing message*s, the code *d335 Producing nonverbal messages* is applied instead, because it has a broader meaning and belongs to the same group Communicating-producing activities).

Table 2.2. Weighting coefficient applied

3FC-ICF-activity	code applied	appearance coefficient		weighting coefficient applied	
		scales of disability	surveys of dependence	scales of disability	surveys of dependence
d325	d315	15%	20%	1.90	1.75
d335	d335	15%	20%	1.90	1.75
d345	d335	15%	20%	1.90	1.75
d360	d350	15%	0%	1.90	0.00
d410	d465	55%	40%	6.96	3.51
d430	d430	20%	20%	2.53	1.75
d440	d440	25%	20%	3.16	1.75
d445	d430	20%	20%	2.53	1.75
d470	d470	20%	80%	2.53	7.02
d475	d475	10%	20%	1.27	1.75
d510	d510	70%	100%	8.86	8.77
d520	d520	70%	80%	8.86	7.02
d530	d530	75%	40%	9.49	3.51
d540	d540	70%	100%	8.86	8.77
d550	d550	75%	60%	9.49	5.26
d560	d560	75%	20%	9.49	1.75
d570	d570	45%	20%	5.70	1.75
d620	d620	20%	80%	2.53	7.02
d630	d630	20%	100%	2.53	8.77
d640	d640	20%	100%	2.53	8.77
d650	d640	20%	100%	2.53	8.77
d660	d660	5%	20%	0.63	1.75
d920	d920	15%	60%	1.90	5.26

The global relevance of each grasp was calculated as the percentage of weighted time of each grasp type out of the total weighted time analysed. In a global analysis, the relevance was calculated by using the two importance scales WCoeff_ScDi and WCoeff_SvDe. Using only the coefficient WCoeff_ScDi, the relevance of each grasp type was also calculated distinguishing by hand involved (left/right), and by whether the action was bimanual or not. Descriptive statistics are presented, and contingency tables and $\chi 2$ computed to check significant differences. More specifically, 2x2 contingency tables were computed for each type of grasp (one grasp/the rest of grasps) versus the hand involved (left/right), and versus the bimanual function (unimanual/bimanual). All the analyses were performed using IBM SPSS Statistics 23.

2.3 Results

The relevance of the different grasps is presented in the graph in Figure 2.3. The highest values corresponded to pad to pad pinch, non-prehensile, cylindrical and lumbrical grasps. The relevance of the grasp types in the scales of disability and in the surveys of dependency differs slightly, especially for the case of the pad to pad pinch grasp. It appears to be much more important than all the other grasps in the scales of disability, while for dependency is at the same level as non-prehensile, cylindrical and lumbrical grasps. Comparing the results from Figure 2.3 with the frequency of daily usage of the grasps27 shown in Table 3, important differences can be observed in the oblique palmar and non-prehensile grasps.

Figure 2.3. Relevance of the different grasps is presented both with Querejeta's scale of 3FC-ICF-activity presence in common tables and scales of disability (ScDi), and with his scale obtained from sociological surveys to take into account patient's perception.

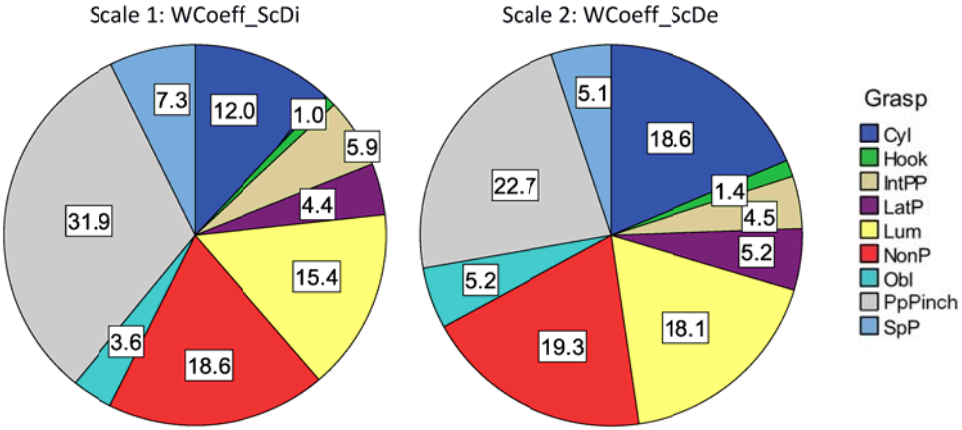
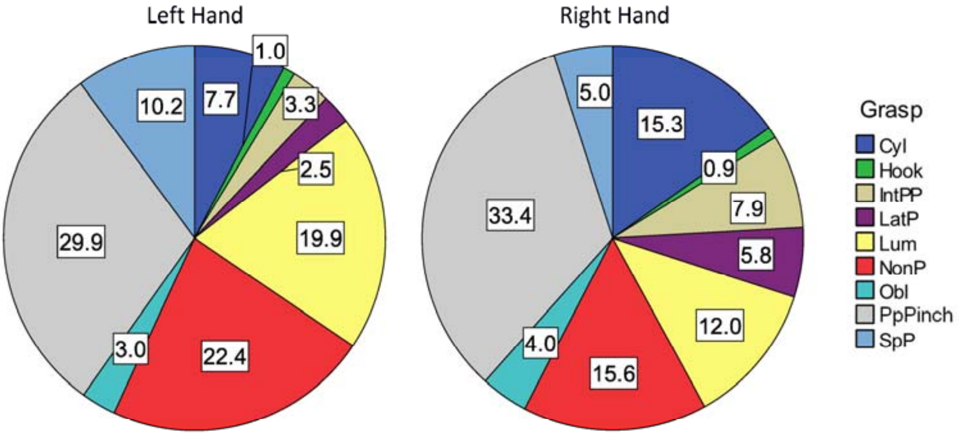


Table 2.3. Percentage of grasp frequency and daily time of use of each grasp type, data from a previous study (Vergara et al. 2014).

	Cyl	Hook	intPP	LatP	Lum	nonP	Obl	PpPinch	SpP
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Grasp Frequency	12.3	2.9	3.3	8.8	9.7	12.7	5.9	38.3	2.8
Daily Time	9.4	2.3	5.8	6.6	10.9	7.6	11.9	36.9	5.7

Relevance of the different grasps distinguishing by hand (left-right), is presented in Figure 2.4. The χ^2 test revealed significant differences for all the grasps, except for hook (bilateral asymptotic significance < 0.05). Thus, the relevance of each grasp is different for the dominant and non-dominant hands, with highest relevance for the pad to pad pinch grasp. The pad to pad pinch grasp was followed in relevance by the non-prehensile and lumbrical grasps for the left hand, far from the rest of the grasp types. However, the cylindrical grasp gained importance for the case of the right hand, being at the same level as the non-prehensile grasp, followed by the lumbrical grasp.

Figure 2.4. Relevance of the different grasps distinguishing by hand (left-right) is presented. ScDi is used.

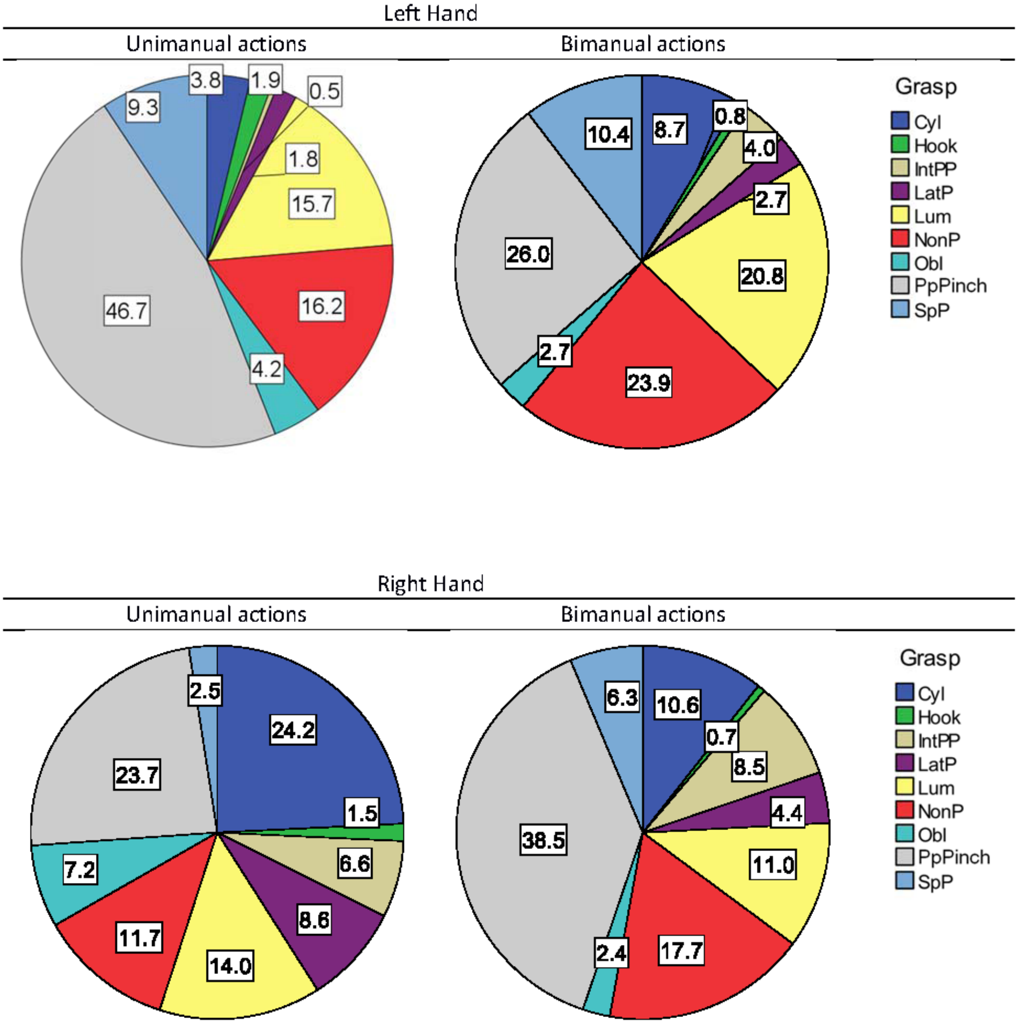


Relevance of the grasps distinguishing by hand (left-right) and by bimanual function is presented in Figure 2.5. The χ^2 test revealed significant differences for all the grasps (bilateral asymptotic significance < 0.05). In the case of the left hand working alone, an important degree of relevance was found for the pad to pad pinch grasp, followed by lumbrical and non-prehensile grasps, whereas, in bimanual tasks, relevancies of these three grasp types were more or less equal. Conversely, in the case of the right hand, relevance of the pad to pad pinch grasp was much higher in bimanual tasks. For the right hand in bimanual tasks, the non-prehensile grasp also showed a high degree of relevance, followed by lumbrical, cylindrical and intermediate power-precision grasps. When the right hand was working alone, similar relevance was observed for the pad to pad pinch and cylindrical grasps, followed by the lumbrical, non-prehensile and lateral pinch grasps.

2.4 Discussion

The comparison of the relevance obtained in this work and the daily frequency usage of each grasp type from a previous study (Vergara et al. 2014) has verified that the most frequently used grasps throughout the day are not the most important grasps for autonomy. The oblique palmar grasp, one of the most used grasps, has been rated with very low relevance for autonomy. This could be due to the large amount of time spent daily on activities such as driving, where the oblique palmar grasp is used for manipulating the steering wheel. Conversely, the non-prehensile grasp is not used so much throughout the day, but it has been rated as the second grasp in terms of relevance for autonomy, probably because of the high weighting coefficient of the 3FC-ICF-activity *d410 Changing basic body position*, where the non-prehensile grasp is present. Nevertheless, the differences between daily time of use and relevance must be taken with care, as the selection of activities was not the same because the purposes of the studies were different.

Figure 2.5. Relevance of the different grasps distinguishing by hand (left-right) and by collaboration (whether hands are collaborating or not) is presented. ScDi is used.



Furthermore, this study has shown a difference between the relevance of some grasp types for scales of disability and for surveys of dependency. Pad to pad pinch is considered in dependency scales as less relevant than in disability surveys, in opposition to cylindrical grasp, therefore giving more importance to perform activities requiring power grasp than to those requiring precision grasp. However, the relative importance of the grasps for autonomy computed in this way only reflects the perception about autonomy from the evaluators of the hand function, and may not match with the patient's perception. Although particular individual's perceptions are affected by the personal habits, roles and responsibilities, more research is desirable to obtain a general scale of dependency of the tasks based on the patient's perception.

It is worth mentioning that the most relevant grasps were found to be the ones in which the thumb is in opposition to the palm and adducted (pad to pad pinch, cylindrical, lumbrical). Within precision grasps, pad to pad pinch is the most relevant, at a great distance from the lateral and special pinches. Within power grasps, cylindrical and lumbrical grasps are the most relevant, much more than the oblique palmar grasp. These three grasps (pad to pad pinch, cylindrical, lumbrical), together with the non-prehensile one, represent almost 80% of relevance for autonomy, which should be considered in rehabilitation strategies. Instead of focusing on ensuring grasp capabilities, physical therapy strategies are usually aimed at improving the AROM and strength, on the basis that maximizing these capabilities will ensure the performance of all grasps required for ADL. The rehabilitation process ends once there is no increase in AROM or strength, with no objective assessment of the actual level of recovery of functionality achieved. Assessing the capability to perform the main grasps for relevance could give an insight into the level of functionality restored.

The most relevant grasps found in this work (pad to pad pinch, cylindrical and lumbrical) are used in the Southampton Hand Assessment Procedure (SHAP) (Light et al. 2002), while the Sollerman hand function test (Brogardh et al. 2007) does not include the lumbrical grasp, based on an estimated 2% percentage of use in ADL, which does not agree with more recent studies27 that report values about a 10%. Current hand function tests could be improved by considering a weighting coefficient of the relevancy of grasp types for autonomy.

The relevance of each grasp has been evidenced to be significantly different depending on the hand, right or left, so that different rehabilitation goals should be considered for dominant and non-dominant hands. The pad to pad pinch, lumbrical and special pinch grasps should be considered more especially in non-dominant hand rehabilitation, whereas pad to pad pinch, cylindrical and lumbrical grasps should be trained in dominant hands.

Moreover, for both left and right hands, the relevance of each grasp types depends on whether the action is bimanual or not. This fact should be taken into consideration when full recovery is difficult. In these cases, rehabilitation should focus on training the most relevant bimanual grasps. In addition, if the dominant hand is severely affected but the other hand remains in good condition, the non-affected one will probably become dominant, and rehabilitation should be oriented in this sense.

Even though valuable new data are provided about the relevance of the different grasp types for autonomy, results should be taken with caution. Some limitations may arise from the set of activities selected, although care was taken to be as representative as possible of the ADL required in developed countries. Furthermore, the results are dependent on the weighting coefficients used, which can differ slightly for different social environments. In particular, weighting coefficients used to rate dependency were obtained from the frequency of appearance in sociological surveys in Spain.

Despite these slight limitations, the results derived from this study could be used as the basis for the development of objective assessment tests, but also to reinforce the rehabilitation process by using serious games, which have been demonstrated as an efficient rehabilitation method (Hocine et al. 2015; Slijper et al. 2014). These games should be focused on training the different grasps according to their importance for autonomy and should be designed so as to be entertaining with the intention of ensuring the player becomes highly involved.

The results obtained in this work might also be useful for prosthesis design. Prostheses should allow performance of the most relevant grasps, as ranked in this study. Furthermore, prosthesis design could be different depending on its use for a dominant or non-dominant hand. However, in the case of a patient who still has a healthy hand, the most appropriate strategy would probably be to always consider the remaining hand as dominant, and design the prosthesis for a non-dominant hand, thereby reinforcing bimanual grasping.

2.5 Acknowledgements

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Chapter
03

INTERDEPENDENCY OF THE MAXIMUM RANGE OF FLEXION-EXTENSION OF HAND METACARPOPHALANGEAL JOINTS

ABSTRACT, KEY TERMS & ABBREVIATIONS

Abstract

Mobility of the fingers metacarpophalangeal joints depends on the posture of the adjacent ones. Current Biomechanical hand models consider fixed ranges of movement at joints, regardless of the posture, thus allowing for non-realistic postures, generating wrong results in reach studies and forward dynamic analyzes. This study provides data for more realistic hand models. The maximum voluntary extension (MVE) and flexion (MVF) of different combinations of metacarpophalangeal joints were measured covering their range of motion. Dependency of the MVF and MVE on the posture of the adjacent metacarpophalangeal joints was confirmed and mathematical models obtained through regression analyzes (RMSE 7.7°).

Key terms

Interdependent limits, finger metacarpophalangeal joint, range of movement, hand biomechanical models.

Abbreviations

MCP	metacarpophalangeal
MVF	maximal voluntary flexion
MVE	maximal voluntary extension
ANOVA	analysis of variance
SD	standard deviation

3.1 Introduction

Biomechanical models of hands have been used for different applications such as in the design of prosthetic hands, studying disabilities, rehabilitation and functional assessment, and for ergonomic product design (Sancho-Bru et al. 2011; Armstrong et al. 2009; Fok & Chou 2010; Valero-Cuevas et al. 2000; van Nierop et al. 2008; Wu et al. 2010; Harih & Tada 2015; Peña-Pitarch et al. 2014; Endo et al. 2014; Park et al. 2014; Hemami et al. 2016). They simulate segments, joints and other tissues (muscles, tendons, ligaments or even skin) and use ranges of mobility at each joint that cover the full range of angles for each joint, regardless of the posture of other joints. However, it is well known that the movements of nearby joints are coordinated (Soechting & Flanders 1997; Engel et al. 1997; Jindrich et al. 2004; Kuo et al. 2006). Lang and Schieber (Lang & Schieber 2004) found that, although both the anatomical structure of the hand and the neuromotor system that control the hand restrict the independence of human finger movements, the anatomical structure limits finger independence to a greater degree. The connections in the flexor-extensor mechanism and the fact that each motor unit actuates more than one tendon makes it unavoidable that fingers move in a coordinated way, which promotes the existence of kinematic synergies in the hand (Santello et al. 1998; Rearick & Santello 2002). Santello et al. (Santello et al. 1998) found a high correlation between joint flexion angles in grasping actions, especially between the closest metacarpophalangeal (MCP) joints, which decreased with the distance between them. Furthermore, a non-linear relationship between the flexion of the MCP and the proximal interphalangeal joints of each finger has been reported (Braido & Zhang 2004).

Therefore, the flexion-extension movement of an MCP joint depends on the angle of the adjacent joints, and this dependency affects the maximal angles in flexion and extension achievable at a specific joint. However, the biomechanical models described in the literature lack this restriction, thereby allowing for highly non-realistic postures. This might generate incorrect results, especially for studying reach of buttons and controls in ergonomic design of tools (e.g. pressing power button of a drill while maintaining it grasped) and for forward dynamic analyzes. The aim of this work is to propose models for the interdependent MCP flexion-extension ranges of movement of the fingers based on experimental data in order to provide more realistic ranges than those currently used for ergonomic design or biomechanical models.

3.2 Methods

Postures of maximum voluntary flexion (MVF) and extension (MVE) of the MCP joints of the four fingers were recorded using a videogrammetric technique (Sancho-Bru et al. 2014) that provides flexion-extension and abduction-adduction rotation angles for each MCP joint. Flexion and ulnar deviations were considered positive.

The experiment, approved by the University Ethical Committee, was performed in two phases: (1) MVE on sample S1 (22 subjects, 11 males and 11 females, 21 right-handed); and (2) MVF on sample S2 (26 subjects, 13 males and 13 females, 23 right-handed). All the participants (Table 3.1) were free of hand lesions or pathologies, were properly informed and gave their written consent. As only eight of the subjects from sample S1 were available at the moment the MVF experiment was performed, both samples S1 and S2 were checked to be comparable (no expectable differences in MVE and MVF between groups). In order to do it, the MVE of the MCP of the index and the little fingers were measured (separately) and the samples compared by means of two analyzes of variance (ANOVAs), one for index MVE and the other for little MVE (dependent variable was the MVE angle, independent variable was the sample).

Firstly, a reference posture (considered as zero rotation angles) was recorded (Figure 3.1, posture R1). For MVE, three starting postures (Figure 3.1) were used: hand lying on a flat surface (R1), and grasping cylinders with a diameter of 65 mm (R2) and 35 mm (R3); while only the flat one (R1) was used for MVF. Maximum voluntary movements of specific fingers (maintaining the other fingers in the three starting postures) were recorded (Figure 3.2): each of the four fingers moving individually (postures ai, bi, ci and di, with i=1 to 4), two adjacent fingers moving (postures ei, fi and gi), three adjacent fingers moving (postures hi and ji) and four fingers moving simultaneously (postures ki). Subindex 1 is used for MVE from the flat starting posture R1 (see figure 3.1), 2 for MVE from R2 posture, 3 for MVE from R3 posture, and 4 for MVF from R1. Movements of non-adjacent fingers were not considered because they are more difficult to perform and previous studies (Santello et al. 2002; Lang & Schieber 2004; Santello et al. 1998) evidence that the closer the finger is, the more influence it has on the MVE/MVF. The cylinders were selected so that the range of extension of the MCP joints in the starting posture goes from 0° (reference position) to approximately 90° (cylindrical grasp with the cylinder with a diameter of 35 mm), passing through an intermediate angle of approximately 45° with the cylinder with a diameter of 65 mm. In the case of MVF, special wooden pieces (Figure 3.2, images with subscript 4) were used to ensure that only the fingers involved in the desired movement flexed. This makes a total of 28 postures for MVE and 10 for MVF, covering a wide range of postures. The abduction angles of the MCP joints and the flexion of the interphalangeal joints were not controlled: each subject adopted the posture in which he/she achieved the MVF or MVE without any indications about the abduction posture. To obtain MVF and MVE values, the postures were maintained for 1 second and the average value of each record was considered.

Table 3.1. Description of samples S1 and S2.

	S1 (MVE)			S2 (MVF)		
	Age (years)	Hand Length (mm)	Hand Breadth (mm)	Age (years)	Hand Length (mm)	Hand Breadth (mm)
Minimum	24	151	68	23	155	72
Maximum	58	197	98	59	194	90
Mean	35.6	171.5	81.6	36.3	178.4	80.3
SD	9.7	12.5	8.2	9.5	10.2	5.4

In the results, the MVE and MVF for each finger have been identified by adding a subindex: 2 for index, 3 for middle, 4 for ring, and 5 for little.

Initially, the means across subjects for each joint were calculated for each of the 38 postures of Figure 3.2 in order to obtain representative statistics data to be compared with data reported in literature. These mean values across subjects were used only for this purpose, and all the data from all subjects was used for all the analyzes described afterwards.

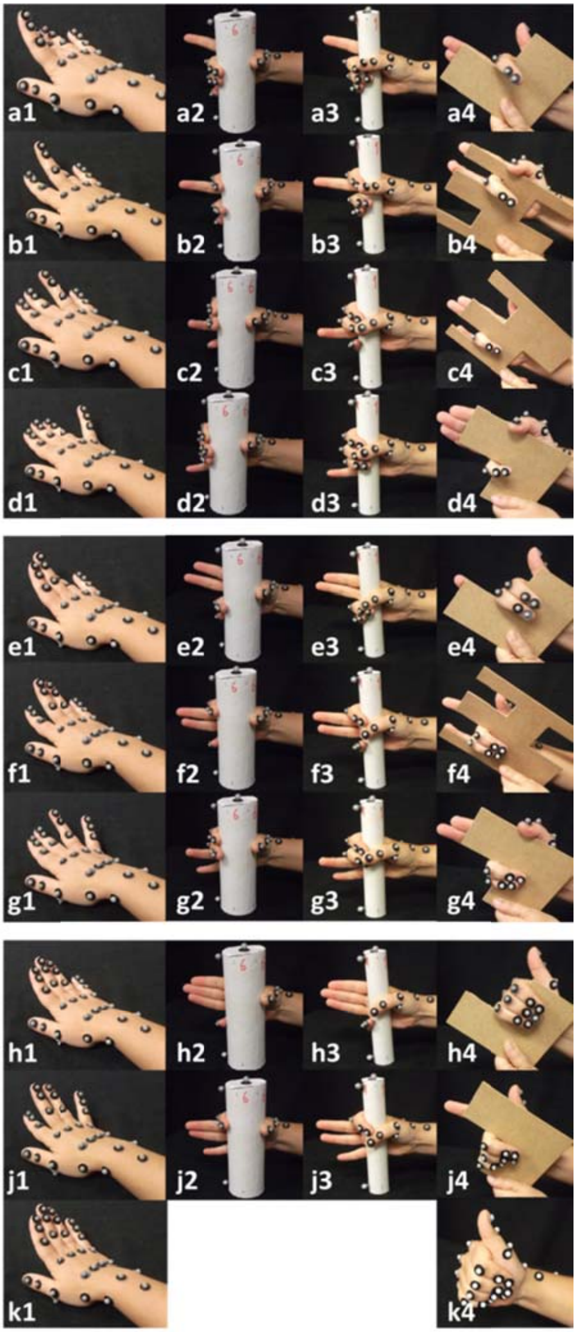
Figure 3.1. Reference postures: R1) hand lying on a flat surface (used as zero rotation angles), and R2) and R3) hand grasping cylinders with different diameters.

Twelve ANOVAs (four fingers x three starting postures) were performed with the data from all subjects to check whether MVE depended on the combination of fingers (dependent variable: MVE of each of the four joints; only factor: combination of fingers). Likewise, four more ANOVAs were performed for the dependent variable MVF. Each ANOVA was performed only with the data obtained while the finger being analyzed was in MVF/MVE, either alone or in combination with others. As an example, for the index finger, the flat starting posture and MVE, the ANOVA was performed with the data for postures a1, e1, h1 and k1, the four possible combinations of fingers in which the index finger moves; for the middle finger, the flat posture and MVF, the ANOVA was performed with the data for postures b4, e4, f4, h4, j4 and k4; and so on. For those cases where significant differences were detected, a post-hoc test was performed (Tukey HSD with p=0.05). Normality of distributions (Kolmogorov-Smirnov test), homogeneity of variances and homoscedasticity (Levene test) were checked previously.

Furthermore, to check the amount of the variability of the data attributable to the subjects, eight univariate ANOVAs (4 fingers x 2 movements -extension and flexion-) were performed with factors ‘subject’ and ‘combination of fingers’ for flexion, and ‘subject’, ‘combination of fingers’ and ‘starting position’ for extension. The F-ratios of the factors were compared.

Eight linear regression analyses were performed with all the data from all subjects to obtain the desired models (dependent variable: the MVF/MVE of each of the 4 joints; independent variables: the flexion angles of all other MCP joints). Each linear regression analysis was performed only with the data obtained while the finger being analyzed was in MVF/MVE, either alone or in combination with others, considering the motions from all starting positions. As an example, the analysis of MVE for the ring finger was performed with data from postures c1, c2, c3, f1, f2, f3, g1, g2, g3, h1, h2, h3, j1, j2, j3 and k1, the dependent variable being the angle of the MCP of the ring finger and the independent variables were the MCP angles of the other three fingers. All the analyses were performed using IBM SPSS Statistics 22 (IBM Corp. ©).

Figure 3.2. Postures for MVE and MVF of MCP joints. The letters refers to the combination of moving fingers, and subindexes refer to the posture of the controlled fingers.



Finally, a verification experiment was developed to check the effectiveness of using the regression equations for two subjects that did not participate in the previous experiment. The subjects were a man (age: 49 years, hand length 184 mm, corresponding to percentile P_{73} of all the participants, and breadth 87 mm, P_{78}) and a woman (age: 41 years, hand length 170 mm , P_{31} of all the participants, and breadth 76 mm , P_{27}). They were asked to perform the MVFs/MVEs in 10 postures (Figure 3.3), six from the previous experiment (three MVF and three MVE) and four others inspired by the American Sign Language, attempting to achieve MVE/MVF of some of the fingers while keeping the others in a comfortable posture. With these equations, different estimations were made for MVF (MVF_5 in postures A and C; MVF_2, MVF_3 and MVF_4 in postures B and C) and for MVE (MVE_1 in postures D, E, F, H and K; MVE_3 and MVE_4 in postures E and F; and MVE_5 in postures F and G). The root mean square error (RMSE) of the differences between the measured MVFs/MVEs (with the videogrammetric technique) and their estimations from the regression equations were calculated.

3.3 Results

The ANOVAs performed to check whether the samples were comparable showed no significant differences ($p=0.293$ for index MVE and $p=0.111$ for little finger MVE).

Table 3.2 shows descriptive statistics (maximum, minimum, mean and standard deviation (SD)) for the means across subjects of the MVF/MVE of the MCP joints. Little finger shows the maximal extension (-37.3°), followed by index finger (-30.2°), while maximal flexion corresponds to the ring finger (89.8°). The dispersions observed within each finger, which are bigger for MVE, are attributable to the posture of the other fingers.

The ANOVAs confirmed that MVF and MVE depend significantly on the combination of fingers involved ($p<0.05$) in the four cases of MVF and in six of the 12 cases of MVE. Figures 3.4 and 3.5 show box plots for MVE and MVF respectively, ordered by mean value, for cases where the differences between the combinations of fingers are significant in the ANOVAs. The horizontal grey-scaled bars in the graphs represent homogeneous groups, i.e. combinations of fingers between which there is no statistically significant difference in MVE/MVF. For example, in the case of the MVE of the index finger and the starting posture R3 (graph at top left) there are significant differences between postures e3 and h3, but there is no significant difference between posture a3 and the other two (e3 and h3).

Figure 3.3. MVE and MVF postures used in the verification experiment for the two subjects. From A) to F) 3 MVF and 3 MVE postures from the previous experiment. From G) to K) postures inspired by the American Sign Language.

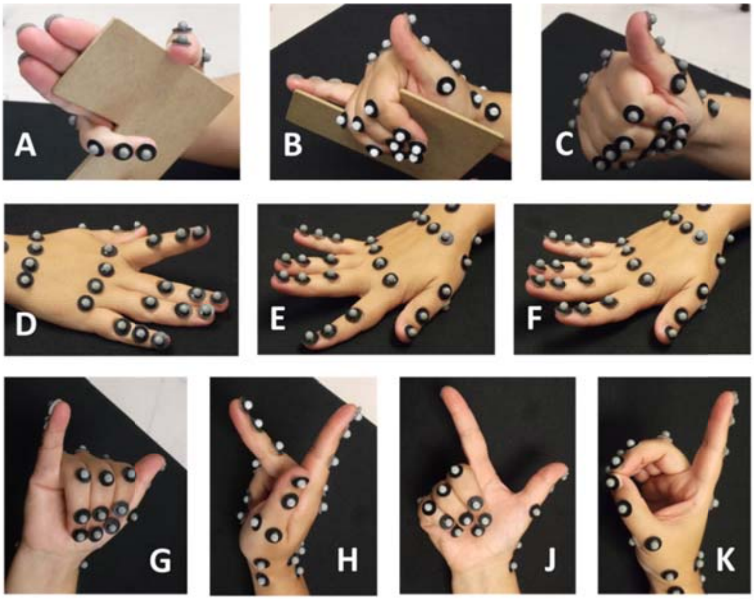


Table 3.2. Descriptive statistics of MVF/MVE for each MCP joint (mean values across subjects). Flexion angles have been considered as positive and extension angles as negative, both in MVF or MVE.

		Maximum (°)	Minimum (°)	Mean (°)	SD (°)
MVE	MCP2	40.2	-30.2	-2.1	21.5
	MCP3	23.9	-25.5	-2.5	18.3
	MCP4	53.5	-25.0	9.0	26.5
	MCP5	11.0	-37.3	-17.4	17.6
MVF	MCP2	76.8	55.6	66.5	8.9
	MCP3	86.1	53.4	67.9	11.4
	MCP4	89.8	52.2	67.5	12.8
	MCP5	85.2	55.1	67.1	12.8

Figure 3.4. Box-plots of MVE for cases in which the differences between the combinations of fingers is statistically significant in the ANOVAs. Boxes represent interquartile ranges (IQR) and medians, while whiskers represent values that are within 1.5 IQR. Circles represent extreme values (out of 1.5 IQR) and stars represent outliers (out of 3 IQR). The horizontal grey-scaled bars represent homogeneous groups. MVEn is the MVE of MCP joint for digit n. Combinations are shown on the horizontal axis with the codes of postures used in figure 3.2.

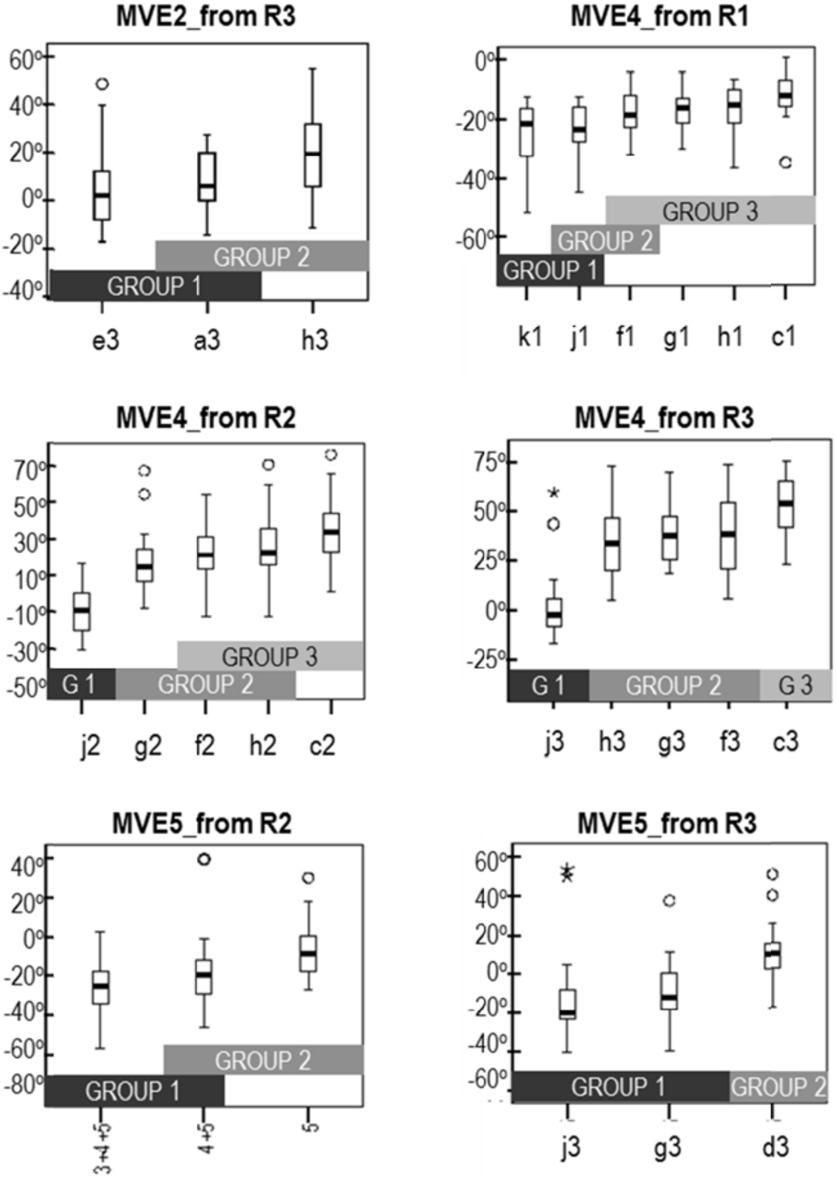
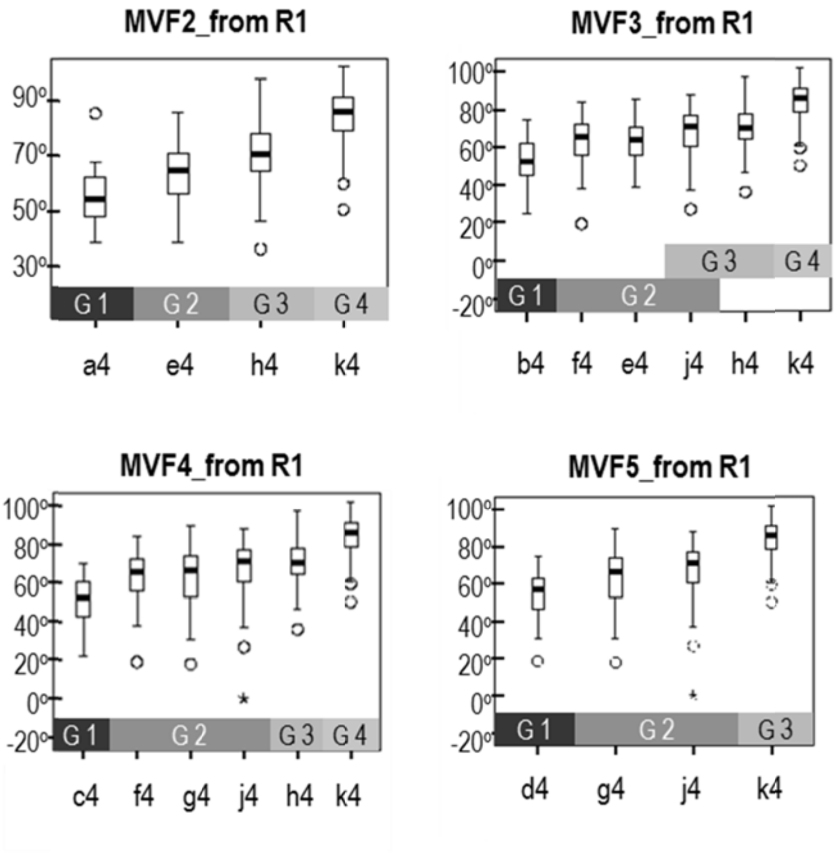


Figure 3.5. Box-plots of MVF for cases in which the differences between the combinations of fingers is statistically significant in the ANOVAs. The horizontal grey-scaled bars represent homogeneous groups. MVFn is the MVF of MCP joint for digit n. Combinations are shown on the horizontal axis with the codes of postures used in figure 3.2.



The F-ratios (table 3.3) of the eight additional ANOVAs showed that the variability attributable to the subject was more than 8 times lower than that attributable to the posture of the other fingers (accounted by the other factors: combination of fingers and starting position).

Table 3.3. F-ratios of the ANOVAs performed to check the variability attributable to the subject in comparison to that due to the posture of other fingers.

		MVE				MVF			
		MCP2	MCP3	MCP4	MCP5	MCP2	MCP3	MCP4	MCP5
Subject		8.5	13.0	8.4	6.5	9.2	9.5	7.0	4.8
Posture of other fingers	Combination of fingers	9.1	2.3	54.4	15.8	50.2	68.5	59.8	42.6
	Starting position	205.4	371.5	476.1	92.6				

Table 3.4 shows the coefficients of the regression equations obtained for the MVE and MVF of each joint, together with adjusted coefficients of determination (adj. R2). All the equations included the constant term so that they can be expressed as:

$$Estimated\ MVFn\ or\ MVEn\ =\ Constant\ +\sum_{\forall\ j\ except\ n} B_j \times MCP_j \qquad (1)$$

where MVF_n is the MVF of the MCP joint for digit n, MVE_n is the MVE of the MCP joint for digit n, MCP_j is the posture of MCP joint j (considering flexion as positive and extension as negative) and Constant and B_j are the coefficients shown in Table 3.3. Note that the regressions are better (higher adj. R2 values) when the number of postures used is bigger: higher values for MVE than for MVF, and for intermediate fingers than for extreme fingers, where the number of postures used are more limited.

Finally, for the verification experiment, the RMSE obtained between the measured and the estimated MVF/MVE was 7.7°.

Table 3.4. Coefficients of the eight regression equations for the MVE and MVF of each MCP joint and adjusted coefficients of determination of each equation (adj.R2). Flexion is considered as positive and extension as negative. As an example:

$MVF_2 = 49.837 + 0.264 * MCP_3 + 0.016 * MCP_4 + 0.039 * MCP_5$.

MVF_n / MVE_n (°)	*Constant* (°)	*B_2*	*B_3*	*B_4*	*B_5*	Adj. R^2
MVF_2	49.8		0.264	0.016	0.039	0.516
MVF_3	46.1	0.203		0.264	0.014	0.705
MVF_4	47.1	0.085	0.178		0.253	0.697
MVF_5	48.4	0.215	-0.056	0.277		0.501
MVE_2	-16.1		0.316	-0.074	0.332	0.618
MVE_3	-10.3	0.489		0.419	-0.065	0.846
MVE_4	2.1	0.016	0.583		0.384	0.897
MVE_5	-24.6	0.254	-0.230	0.605		0.613

3.4 Discussion

The maximum values for the means of the MVE/MVF (negative for extension and positive for flexion) shown in Table 3.2 are similar to the values of ranges of mobility reported in the literature (90° flexion, 30-40° extension (Kapandji I.A. 2007)). The mean MVE/MVF values shown in Table 3.2 are highly variable, as can be observed from the SD values and the minimum and maximum values. This high variability is not attributable to subjects, as the means have been obtained across subjects, but is due to the different postures considered for the other fingers, as it is reinforced by the ANOVAs and the F-ratios obtained. The dispersion of the mean MVE values is much higher than that of the MVF values, thus implying a higher dependency on the extension range of movement than on the flexion one. This can be explained by the constraints introduced by the juncturae tendinum connecting the extensor tendons on the hand metacarpals (Lang & Schieber 2004; Santello et al. 1998), which is not present for the case of the flexor tendons in the palmar side of the hand. All these evidences highlight the fact that the fixed limits on the ranges of motion of the MCP joints used in existing models in literature are non-realistic and that better estimates of the inter-dependability of adjacent MCP postures are needed. Moreover, this study evidences that the

MVE/MVF for the MCP joints depends on the combination of fingers involved in the movement in most cases and, as can be observed from the magnitude of the regression coefficients, generally, the closer the finger is, the more influence it has on the MVE/MVF, in agreement with other studies (Lang & Schieber 2004; Santello et al. 1998; Santello et al. 2002). Again, this can be explained by the existing connections (juncturae tendinum and intertendinous fascia) between adjacent tendons. This has biomechanical and ergonomics implications. For example, postures with extreme flexion/extension of a particular MCP joint not accompanied by adjacent joints should be avoided in order to prevent high stresses arising from tight connections. This can occur when the grasping of an object has to be maintained with some fingers while other finger or fingers have to perform another action such as pressing a control button. Looking at the regression equations it can be observed that all the signs of the adjacent fingers are positive and have the biggest coefficients. This means that MVF (positive sign in the equation) is increased when adjacent fingers are more flexed, while in the case of MVE (negative sign) is reduced when adjacent fingers are more flexed. I.e., fingers tend to move together to the same direction maintaining a maximum relative flexion between adjacent MCP joints, and this maximum relative posture between fingers seems to determine the MVE/MVF that adjacent fingers can achieve.

The different orientations of the juncturae tendinum of the extensor tendons of the fingers (Abdel-Hamid et al. 2013; von Schroeder & Botte 2001) become in different constraints among fingers. Extension of the middle MCP joint is similarly constrained regardless of the posture of the other fingers, so that no significant dependency was observed on the combination of fingers involved for any of the reference postures. Oppositely, ring MCP joint showed significant dependency for all reference postures, little MCP joint for the two most flexed reference postures, and index MCP joint only for the most flexed reference posture. Highest differences in all cases were found between the case in which only one finger was extended while the other ones were kept fixed, and the case in which three adjacent fingers were extended while only one finger was kept fixed.

The juncturae tendinum of the extensor tendons of the fingers may also introduce MCP flexion constraints among fingers, depending on the orientation of the juncturae tendinum, as flexion requires excursion of the extensor tendon (von Schroeder & Botte 2001). This orientation highly depends on the relative flexion between adjacent MCP joints. As a consequence, significant dependency on the combination of fingers involved was observed for flexion of all MCP joints.

The significant differences in Figures 3.4 and 3.5, modelled using the regression equations, are in accordance with the physiological constraints provided by the juncturae tendinum connecting the extensor tendons (Lang & Schieber 2004; Santello et al. 1998). For example, the connection from the middle to the index tendon, according to physiological observation (Abdel-Hamid et al. 2013), inserts more proximally into the middle tendon than into the index one when both fingers present a similar MCP joint angle (as in posture R1). Such orientation tends to limit index MCP flexion. As the middle finger flexes with respect to the index, such orientation tends to get inverted and can even generate an extension limitation on the index MCP joint. This is why MVF_2 only presented significant differences when starting from posture R1, for which maximal flexion of the index finger was much lower when moving alone than when accompanied by the middle finger and, alternatively, MVE_2 presented significant differences only when starting from the most flexed posture, R3.

The main limitation of this work is that the proposed model has been obtained using a limited, although varied, number of postures and the postures of the interphalangeal joints were not controlled (any flexion at these joints would generate an extra excursion of the extensor tendon, and a smaller one for the flexor tendons, which could have a slight effect on the MVE/MVF of the MCP joints). The ranges of motion estimated with the models proposed should be considered, thus, as indicative limits of such ranges of motions with a small error (the error for the 2 subjects in the validation experiment was low).

Furthermore, estimation of MVF was performed using wooden pieces that restricted the motion of other fingers, as these postures can only be reached using such a restriction. In a similar way, for MVE cylinders were used, and the fingers were restricted by exerting a force squeezing them. This fact sets a limitation, but only when using these data for free movements, not for grasping objects, as the types of restrictions used in this work are present when the hand is using objects and therefore more appropriate for grasp analysis.

The regression models proposed for the MCP flexion-extension range of movements provided good estimations for subjects that did not belong to the samples used to obtain the regression equations and can be easily implemented in existing biomechanical models to provide more realistic ranges than those currently used. The proposed models can benefit the existing biomechanical models used for very different applications, such as for the study of reach in ergonomic design, but could also be useful as reference values in clinical or rehabilitation assessments.

Future work could address obtaining complementary regression models using non-restricted starting postures, more appropriate for being used in realistic animation involving free finger movements.

3.5 Conclusion

This study has shown that the MVE/MVF for each MCP joint depends on the posture of MCP joints of the other fingers. Generally, the closer the finger is, the more influence its MCP joint angle has on the MVE/MVF.

Mathematical models are provided for quantifying this interdependency, yielding good estimations. These estimates should be considered as indicative limits, as they could be slightly modified because of the effect of the position of the IP joints.

The models proposed could benefit existing biomechanical models, providing more realistic ranges for their application. The data provided could also be useful as reference values in clinical or rehabilitation assessments.

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Chapter
04

ACROSS-SUBJECT CALIBRATION OF AN INSTRUMENTED GLOVE TO MEASURE HAND MOVEMENT FOR CLINICAL PURPOSES

ABSTRACT, KEY TERMS & ABBREVIATIONS

Abstract

Motion capture of all degrees of freedom of the hand collected during performance of daily living activities remains challenging. Instrumented gloves are an attractive option because of their higher ease of use. However, subject-specific calibration of gloves is lengthy and has limitations for individuals with disabilities. Here, a calibration procedure is presented, consisting in the recording of just a simple hand position so as to allow capture of the kinematics of 16 hand joints during daily life activities even in case of severe injured hands. 'across-subject gains' were obtained by averaging the gains obtained from a detailed subject-specific calibration involving 44 registrations that was repeated three times on multiple days to 6 subjects. In additional 4 subjects, joint angles that resulted from applying the 'across-subject calibration' or the subject-specific calibration were compared. Global errors associated with the 'across-subject calibration' relative to the detailed, subject-specific protocol were small (bias: 0.49º; precision: 4.45º) and comparable to those that resulted from repeating the detailed protocol with the same subject on multiple days (0.36º; 3.50º). Furthermore, in one subject, performance of the 'across-subject calibration' was directly compared to another fast calibration method, expressed relative to a videogrammetric protocol as a gold-standard, yielding better results.

Key terms

Instrumented glove, across-subject calibration, fast calibration, hand movement, hand disabilities.

Abbreviations

ADL	Activities of daily living
ANN	Artificial neural networks
AROM	Active range of motion
ASL	American sign language
CMC1	Carpometacarpal joint of thumb
DIP2 to DIP5	Distal interphalangeal joints (2 to 5, index to little digits)
DoF	Degree of freedom
HB	Hand breadth
HL	Hand length
IP	Interphalangeal joint

IP1	Thumb interphalangeal joint
MCP	Metacarpophalangeal joint
MCP1 to MCP5	Metacarpophalangeal joints (1 to 5, thumb to little digits)
PIP2 to PIP5	Proximal interphalangeal joints (2 to 5, index to little digits)
RMSE	Root mean square error
SD	Standard deviation

4.1 Introduction

The ability of the human hand to grasp and manipulate objects is a key factor determining an individual's ability to complete a great number of activities of daily living (ADL) as well as of working life (Bullock et al. 2013; Zheng et al. 2011; Vergara et al. 2014). The versatility of the human hand is possible thanks to the complex kinematics of the system: 25 degrees of freedom (DoFs) controlled by muscles, tendons and ligaments (Brand & Hollister 1999). Measurement of complex hand movements is useful for numerous applications, including functional assessment of the pathological hand and its rehabilitation (Chiu et al. 2000; Nathan et al. 2009; Oess et al. 2012), analysis of sporting techniques and ergonomics of tools, the study of human motor control strategies, and robotics (Grinyagin et al. 2005; Sanchez-Margallo et al. 2010; Tripp et al. 2006; Griffin et al. 2000).

Different methods can be used to measure hand movement, but most of them fail when applied to the simultaneous measurement of all hand DoFs while performing functional ADL. Goniometers do not allow for the simultaneous measurement of all DoFs. Electromagnetic systems (Mitobe et al. 2006) are susceptible to magnetic and electrical interference from metallic objects in the environment. Marker-based optical systems provide high accuracy (Sancho-Bru et al. 2014), but they can be used only within the area covered by the cameras, require a substantial amount of time to setup the markers, and markers often become occluded during the recording of tasks. Markerless optical motion capture (Metcalf et al. 2013) and inertial systems (Kortier et al. 2014) are frequently adopted in virtual reality games, but even though great enhancements in accuracy are being done (O 'flynn et al. 2015), no commercial devices are currently available according to our knowledge. At this point, instrumented gloves seem to be the most effective method for collecting data from all finger joints continuously, without occluding problems, and with no special environmental constraints (Buffi et al. 2014).

Despite the relative strengths described above, the use of instrumented gloves is also problematic, primarily due to difficulties associated with the calibration processes needed to obtain the gains for the individual sensors that record each DoF. On the one hand, gloves include a high number of sensors to be calibrated. And on the other hand, some of the sensors do not have a linear relationship with the angle to be measured, as is the case of the abduction sensors at metacarpophalangeal joints, which are affected by the relative flexion between adjacent metacarpophalangeal joints. In order to correct this effect, a subject-specific calibration obtained by positioning the fingers in specific angles of combined flexion/extension and abduction angles spanning the entire range of motion has been shown to provide good accuracy (Eccarius et al. 2012). However, this method requires subjects to pose in a large number of postures, along with recording controlled movements, limiting its feasibility for use in real, clinical applications and large-scale field studies. This issue is especially problematic when dealing with patients with disabilities that interfere with the capacity to achieve postures needed for the calibration. In contrast, optimization methods have been used in an attempt to minimize the number of postures/movements required for the calibration (Griffin et al. 2000): each finger and the thumb are repeatedly flexed and extended while maintaining digit tip contact (close loop method), and the gains are optimized such that the joint angles obtained from an underlying model best maintained digit tip contact throughout the task. However, when evaluated against a gold-standard, low accuracy was observed (Buffi et al. 2014). In a third approach, artificial neural networks (ANN) have been used to estimate sensor gains from an individual subject's hand segment lengths (Zhou et al. 2010). However, this approach requires a large number of previously performed manual calibrations on many subjects, spanning a broad range of different segment lengths. In addition, as no angular errors were reported, it is unclear whether the lengths of hand segments are enough to yield high quality data (Zhou et al. 2010).

In brief, subject-specific instrumented glove calibration procedures are lengthy and not applicable to patients with some disabilities. In this work we test whether an 'across-subject calibration', defined via detailed, accurate, yet lengthy calibration from a small number of subjects, yields valid data when applied to additional subjects via registration of a single, simple reference posture.

4.2 Methods

The experiment, approved by the University's Ethical Committee, was developed in three phases. First, a very detailed calibration protocol was applied several times to 6 subjects. The gains obtained through this detailed calibration process were then used to define an 'across-subject calibration'. In a separate group of an additional 4 subjects, the joint angles that resulted from applying this 'across-subject calibration' were compared to those that resulted from transforming the identical set of sensor outputs to joint angles via the detailed, subject-specific calibration method. Finally, in one subject, the errors associated with the across-subject calibration were directly compared to those from another fast calibration method (Buffi et al. 2014). In this case, errors were expressed relative to a previously validated videogrammetric protocol (Sancho-Bru et al. 2014). All the errors and comparisons were made on the calculated angles of five different static postures. All the participants were right-handed, free of hand lesions or pathologies and gave informed consent to participate. The instrumented glove used was a right-hand

Cyberglove (Cyberglove Systems LLC; San Jose, CA), one sized, with 18 resistive flex sensors and 8-bit digital signal output proportional to the underlying bending angle (Figure 4.1). Only outputs from 16 sensors were used in this experiment, discarding the two sensors of the wrist.

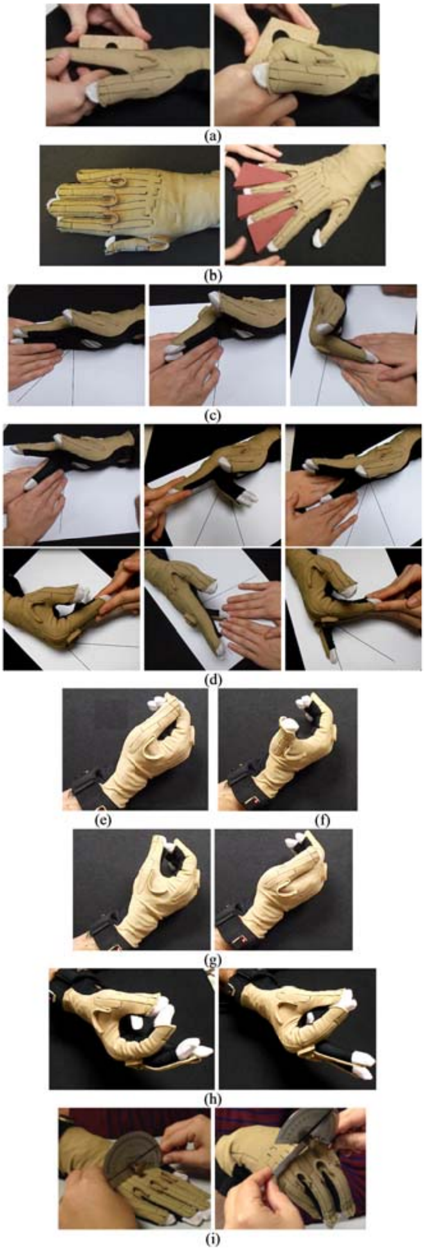
Figure 4.1. 18-sensor Cyberglove sensor location (the two sensors related to the wrist are not sketched as they are not used)

4.2.1 Calibration protocols

4.2.1.1 Detailed calibration protocol

Our protocol combines procedures based on several previous works (Buffi et al. 2013; Eccarius et al. 2012; Griffin et al. 2000), and consists in registering 44 different poses or guided movements (Figure 4.2). The first 20 calibration trials correspond to the calibration of 10 individual flexion sensors (two static postures per sensor, F1 to F10, see Fig. 4.1) to measure flexion at all metacarpophalangeal (MCP1 to MCP5; 1 to 5, thumb to little digit, respectively) and interphalangeal (IP1 and PIP2 to PIP5) joints (Figure 4.2.a). Gains of these flexion sensors (G_F) assume a linear relationship between the flexion angle at these joints and the glove output signals (Kessler et al. 1995; Zhou et al. 2010; Eccarius et al. 2012). Each MCP joint of the fingers and all IP joints were calibrated at 0º and 75º by pressing custom-made wood tools against the dorsal aspect of the digit. MCP1 was calibrated at 0º and 35º.

Figure 4.2. Postures and guided movements used for the calibration protocol: (a) Examples of calibration trials 1 to 20; (b) Trials 21 and 22; (c) Starting postures of trials 23 to 25; (d) Examples of trials 23 to 40; (e) Neutral extension and abduction for trials 41 and 42; (f) Maximal extension during trial 41; (g) Maximal abduction (left) and adduction (right) during trial 42; (h) closed loop movement during trial 43; (i) Measurement of little CMC flexion in trials 21 (left) and 44 (right)



Trials 21 and 22 (Figure 4.2.b) were used to obtain the gains of A2 to A4 sensors (G_A), corresponding to relative abduction of MCP2 to MCP5, also assuming a linear relationship. Both trials correspond to static postures with the hand resting flat on a table, the first with the fingers close together, defined to be 0º for the three abduction angles, and the second with custom-made wedge tools inserted firmly between the fingers that constrained the relative abduction angles to 25º, 16º and 17º for MCP2, MCP4 and MCP5, respectively.

Previous studies have warned about the cross-coupling effect between abduction and flexion MCP angles: due to the physical configuration of the glove, the output signal of abduction sensors varies when the adjacent MCP joints flex, even with no variation of the abduction angle, so that the abduction angle needs a correction (Eccarius et al. 2012; Zhou et al. 2010). We confirmed that a second order polynomial of the flexion angles of adjacent MCP joints provides a good correction for abduction angles, in accordance with Eccarius et al. (Eccarius et al. 2012). The 5 polynomial coefficients of the correction term (C_1, C_2, C_3, C_4 and C_5) at each sensor were obtained through an optimization process, by minimizing the root mean square error (RMSE) of the abduction angles measured during six motions with 0º of abduction. In the case of index-middle abduction, the subject performed three extension-flexion cycles of the index finger with no abduction, while the others three fingers were kept fixed at different MCP flexion angles: 0º, 40º and 80º, (Figure 4.2.c, trials 23 to 25) and then three extension-flexion cycles of the middle, ring and little fingers together, while the index finger was fixed at the same three MCP angles (0º, 40º and 80º), with no abduction (trials 26 to 28). Analogous corrections have been considered for the abduction of MCP4 and MCP5, through trials 29 to 34, and 35 to 40, respectively (Figure 4.2.d).

The positions of A1 and Roll1 sensors do not correspond exactly to either flexion or abduction of the thumb carpometacarpal (CMC1) joint (Kramer 1996), making obtaining these joint angles difficult (Crasborn et al. 2006). For CMC1 flexion, we have considered a linear relationship (gain G_F) with Roll1 plus an adjustment factor (AF_F) with A1 sensor. The adjustment factor was obtained by minimizing the RMSE of the abduction angles, assumed to be zero, in trial 41, which consists in extending the thumb from neutral (Figure 4.2.e) to maximal extension (Figure 4.2.f), and returning to neutral. Analogously, for CMC1 abduction, a linear relationship (gain G_A) with A1 plus an adjustment factor (AF_A) with Roll1 sensor was considered. The adjustment factor was obtained by minimizing the RMSE of the flexion angles, assumed to be zero, in trial 42, which consists in abducting the thumb from neutral (Figure 4.2.e) to maximal abduction, then to the maximal adduction (Figure 4.2.g), and returning to neutral abduction. Once the adjustment factors were calculated, the gains for both linear relationships (G_F and G_A) were obtained from trial 43, which consists in three consecutive closed loop motions made between index finger and the thumb, repeatedly flexing and extending both digits while maintaining tip contact (Figure 4.2.h). The gains were calculated so that the joint angles obtained from the underlying kinematic model (Sancho-Bru et al. 2012) best maintained digit tip contact throughout the task. Index distal interphalangeal (DIP2) flexion angle, not provided by the Cyberglove used in this work, is required for computing the distance between the thumb and index finger tips. This angle was estimated from the PIP2 angle by using the linear regression experimentally obtained with the videogrammetric technique (Sancho-Bru et al. 2014) over 8 subjects performing the same loop movements ($DIP2 = 0.87 \cdot PIP2 - 25.27^o$).

Finally, palmar arch is estimated from Roll2 assuming a linear relationship (gain G_F) with two postures: previous trial number 21 (palm extended, 0º) and trial 44 (palm flexed). In this case, the angle between index-middle knuckles and ring-little knuckles was measured for each subject using a manual goniometer (Figure 4.2.i).

4.2.1.2 Fast calibration protocol

This protocol, based on a previous one (Buffi et al. 2014), consists in registering 12 different poses or guided movements. Four trials consist in closed loop motions made between index, middle, ring and little fingers and the thumb, respectively, repeatedly flexing and extending both digits while maintaining tip contact; and they were used to adjust gains of all flexion angles (all G_F) and the abduction of thumb CMC together with both adjustment factors (AF) so that the joint angles obtained from the underlying kinematic model (Sancho-Bru et al. 2012) best maintained digit tip contact throughout the tasks. Again, DIP flexion angles were estimated from the fingers PIP angles by using linear regressions experimentally obtained as with DIP2 ($DIP3 = 0.79 \cdot PIP3 - 18.33^o$; $DIP4 = 0.73 \cdot PIP4 - 20.54^o$; $DIP5 = 0.84 \cdot PIP5 - 12.42^o$).

For abduction of MCP joints of fingers the same procedure as in the detailed protocol was applied to obtain G_A, using analogous postures to trials 21 and 22; but a shortened protocol was applied for the cross-coupling effect, as only the extension-flexion cycles corresponding to 0º in MCP flexion of the fixed digits (two trials per sensor) were used.

4.2.1.3 Across-subject calibration protocol

The across-subject protocol involved calculating 'across-subject gains' by averaging the gains and coefficients that resulted from the *Detailed calibration protocol* implemented in a group of 6 subjects (see below, Experimental procedure and analysis, Phase 1).

Joint angles were calculated using sensor outputs relative to the outputs of trial 21, which was defined as 0º for all joints. If S_{sensor} is the relative output signal of *sensor*, then the angles at the different joints are calculated as follows.

IP1, PIP2 to PIP5, and $\mathrm{MCP1}_{\mathrm{f}}$ to $\mathrm{MCP5}_{\mathrm{f}}$, angles:

$$Flexion\ Angle = G_F \cdot S_{sensor} \tag{1}$$

Palmar arch angle:

$$Palmar\ arch\ Angle = GPalmar \cdot Roll2 \tag{2}$$

MCP2 to MCP5 abduction angles:

$$MCP2_A = G_{A2} \cdot S_{A2} + (C_{1_{MCP2}} \cdot S_{F3} + C_{2_{MCP2}} \cdot S_{F5} + C_{3_{MCP2}} \cdot {S_{F3}}^2 + C_{4_{MCP2}} \cdot {S_{F5}}^2 + C_{5_{MCP2}} \cdot S_{F3} \cdot S_{F5}) \tag{3}$$

$$\mathrm{MCP3}_{\mathrm{A}} = 0 \tag{4}$$

$$MCP4_A = G_{A3} \cdot S_{A3} + (C_{1_{MCP4}} \cdot S_{F5} + C_{2_{MCP4}} \cdot S_{F7} + C_{3_{MCP4}} \cdot {S_{F5}}^2 + C_{4_{MCP4}} \cdot {S_{F7}}^2 + C_{5_{MCP4}} \cdot S_{F5} \cdot S_{F7}) \tag{5}$$

$$MCP5_A = MCP4_A + G_{A4} \cdot S_{A4} + (C_{1_{MCP5}} \cdot S_{F7} + C_{2_{MCP5}} \cdot S_{F9} + C_{3_{MCP5}} \cdot {S_{F7}}^2 + C_{4_{MCP5}} \cdot {S_{F9}}^2 + C_{5_{MCP5}} \cdot S_{F7} \cdot S_{F9}) \tag{6}$$

Thumb CMC flexion and abduction angles:

$$CMC1_F = G_{F_{CMC1}} \cdot (Roll1 + AF_F \cdot A1) \tag{7}$$

$$CMC_{1_A} = G_{A_{CMC1}} \cdot (A1 + AF_A \cdot Roll1) \tag{8}$$

4.2.2 Experimental procedure and analysis

Phase 1. The Detailed calibration was applied to 6 subjects, selected to achieve a representative variation in hand size (Table 4.1, Sample 1, Subjects 1 through 6). After calibration, sensor outputs were recorded while each subject adopted five static postures (Figure 4.3), selected to represent different postures incorporating both flexion and abduction of fingers. Each subject repeated the entire process, including calibration and static postures, in three different sessions. The gains and coefficients were calculated from the detailed calibration protocol for each subject and session. The joint angles of the five static postures were estimated from the sensor outputs collected during a given session three times: first, using the gains and coefficients from the corresponding calibration (same session in which the posture was measured); then, from the distinct calibrations resulting from the other two repeated sessions. The differences in the angles that result from transforming the same sensor output with gains from the three repeated calibrations serves as an estimate of the error of using a subject-specific, detailed calibration obtained in a different experimental session and has implications for the need to replicate the calibration for a given subject if testing involves multiple sessions. Mean and standard deviation (SD) across postures and subjects of the paired differences were used as bias and precision errors, respectively. Errors were also evaluated by grouping some of the hand joint movements for a broader interpretation: flexion at all MCP joints, flexion at all IP joints, and abduction at all MCP joints.

After completion of all testing (6 subjects x 3 sessions) and analysis in Phase 1, the 'across-subject gains' for the across-subject calibration protocol were defined as the mean values of all the gains and coefficients.

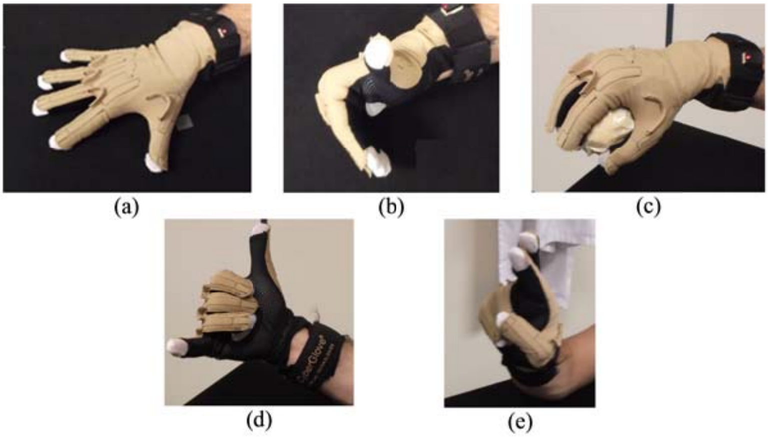
Table 4.1. Descriptive data of all the subjects participating in the experiments

		Gender	HL (mm)[a]	HB (mm)[b]
Sample 1	Subject 1	Male	183	88
	Subject 2	Female	169	76
	Subject 3	Male	176	81
	Subject 4	Female	160	69
	Subject 5	Male	196	83
	Subject 6	Female	179	76
Sample 2	Subject 7	Male	171	86
	Subject 8	Female	166	73
	Subject 9	Male	204	82
	Subject 10	Female	176	74

[a] HL: hand length, measured from the proximal palmar crease to the tip of the middle finger)

[b] HB: hand breath, measured at the metacarpal heads

Figure 4.3. Static postures used to evaluate the errors of the method proposed: (a) Maximal abduction of all fingers with hand in a plane; (b) All fingers in 90° MCP flexion while thumb in maximal extension; (c) Grasping a ball; (d) Letter 'Y' from American Sign Language (ASL); (e) Letter 'R' from ASL



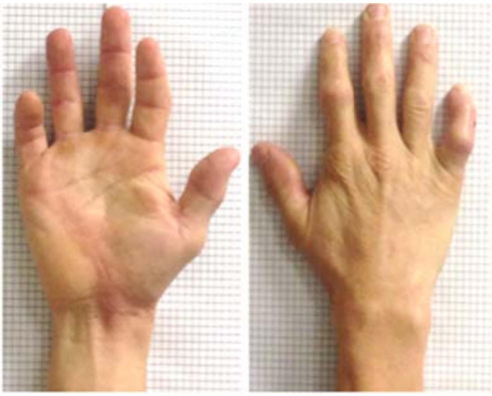
Phase 2. Four additional subjects (Table 4.1, Sample 2, Subjects 7 through 10) were tested in a single session, using the detailed calibration protocol and the same five static postures. The joint angles for each posture were calculated from the sensor output two times in Phase 2: first, using the gains and coefficients resulting from the detailed calibration performed for the subject in the testing session; then, from the across-subject calibration that resulted from Phase 1. Differences between these angles (across-subject minus detailed) provide an estimate of the error of using the 'across-subject calibration' protocol compared to using a detailed subject-specific protocol. Again, mean and SD across postures and subjects of the differences were considered as bias and precision errors. Errors were also evaluated across the grouped hand movements described in Phase 1.

To evaluate the dependence of errors associated with the across-subject calibration on hand-size, Pearson correlations of the precision errors with hand breadth (HB) and hand length (HL) were calculated for each joint angle. The global postures were also visualized using a kinematic hand model developed in previous work (Holzbaur et al. 2005; Buffi et al. 2013) comparing both calibrations for each posture and subject.

Phase 3. For a single subject (Subject 9), the errors resulting from the across-subject calibration and the fast calibration protocol were calculated relative to a reference data set, quantified in a separate protocol, using a videogrammetric technique thoroughly detailed in a previous work (Sancho-Bru et al. 2014). Because the hand could not be effectively instrumented with the markers needed for the videogrammetric method while simultaneously wearing the instrumented glove, two datasets were collected; the first dataset was collected while the subject was wearing the glove, the second dataset was collected without the glove. Each data set consisted of three trials of each of the five static postures described previously. For the across-subject and fast calibration protocols, joint angles were estimated from the first dataset, using the identical sensor output to calculate the joint angles according to the gains resulting from the respective calibration method. In all comparisons, the average joint postures across all three repetitions for a given posture were compared. The accuracies (bias and precision errors) of the across-subject and fast protocols were calculated as the differences between the angles measured using the respective calibration and the videogrammetric dataset. Notice that the 'R' American Sign Language (ASL) posture (Figure 4.3.e) was not included, as it couldn't be measured with the videogrammetric technique because of markers and fingers overlapping.

Phase 4. Finally the clinical utility of the across-subject calibration was tested on a subject with a severely injured hand (dominant hand) caused by an accident with a circular saw, in an advanced recovering stage (Figure 4.4). The protocol was used to measure the active range of motion (AROM) of his hand joints. His AROM values were compared to the normal values measured with the same protocol to a sample of 24 healthy subjects.

Figure 4.4. Right hand of the injured subject.



4.3 Results

Phase 1. Global bias and precision errors associated with transforming the same sensor output with gains obtained from three, distinct, detailed subject-specific calibrations obtained in repeated sessions are small (0.36° and 3.50°, respectively; Table 4.2). Highest bias (3.19°) corresponded to abduction of little MCP joint, and highest precision error (12.66°) to flexion of thumb CMC joint, followed by palmar arch. Very low precision error is observed for IP and MCP flexion angles (2.71° and 1.62°, respectively), and slightly higher for MCP abduction angles (3.52°).

Phase 2. Global bias and precision errors associated with using the 'across-subject calibration' protocol compared to using a detailed subject-specific protocol are similar to those obtained in Phase 1 (0.49° and 4.45°, respectively; Table 4.2). Again, highest bias corresponded to abduction of little MCP joint (4.86°), highest precision errors to CMC joint angles and abduction of little MCP joint (about 10°). Precision errors for IP and MCP flexion angles are very small (1.70° and 2.67°, respectively). Precision errors associated with abduction of MCP joints are somewhat larger. The differences for the worst case are graphically visualized in Figure 4.5.

Table 4.2. Mean bias and precision errors, in degrees, of using gains and coefficients obtained with the detailed calibration in a different session for subjects of sample 1 (phase 1), and of using the across-subject calibration versus the detailed subject-specific calibration (phase 2)

	Phase 1			Phase 2		
Joint	Bias (º)	Precision (º)	Mean Precision of group of joints (º)	Bias (º)	Precision (º)	Mean Precision of group of joints (º)
IP1$_{f}$	0.01	1.33	2.71	-0.03	1.72	1.74
PIP2$_{f}$	-0.02	2.88		0.04	2.47	
PIP3$_{f}$	0.02	3.76		-0.41	1.34	
PIP4$_{f}$	0.01	4.00		0.72	1.70	
PIP5$_{f}$	1.32	1.59		-0.35	1.48	
MCP1$_{f}$	0.00	0.92	1.62	0.84	4.90	2.67
MCP2$_{f}$	-0.05	2.21		-0.23	2.10	
MCP3$_{f}$	0.00	2.15		2.26	3.00	
MCP4$_{f}$	-0.01	1.76		0.19	1.44	
MCP5$_{f}$	0.92	1.04		-1.51	1.91	
MCP2$_{a}$	-0.25	4.77	3.52	0.2	5.34	7.90
MCP4$_{a}$	0.00	3.31		-0.4	8.19	
MCP5$_{a}$	3.19	2.47		4.86	10.16	
CMC1$_{f}$	-1.26	12.66		1.78	10.26	
CMC1$_{a}$	0.08	2.88		2.18	10.39	
Palmar arch	1.79	8.19		-0.18	4.85	
Grand Mean	0.36	3.50		0.49	4.45	

Joint angle errors were significantly correlated with hand size, especially for PIP and MCP flexion angles (cf., Fig. 6, shaded cells indicate significant Pearson correlations). In general, we observed stronger correlations with measures of hand length compared to breadth.

Figure 4.5. Visual comparison of the five static postures for the subject 9, the one with the highest differences (detailed subject-specific calibration versus across-subject calibration). (a) Maximal abduction of all fingers; (b) All fingers in 90° MCP flexion while thumb in maximal extension; (c) Grasping a ball; (d) Letter 'Y' from American Sign Language (ASL); (e) Letter 'R' from ASL

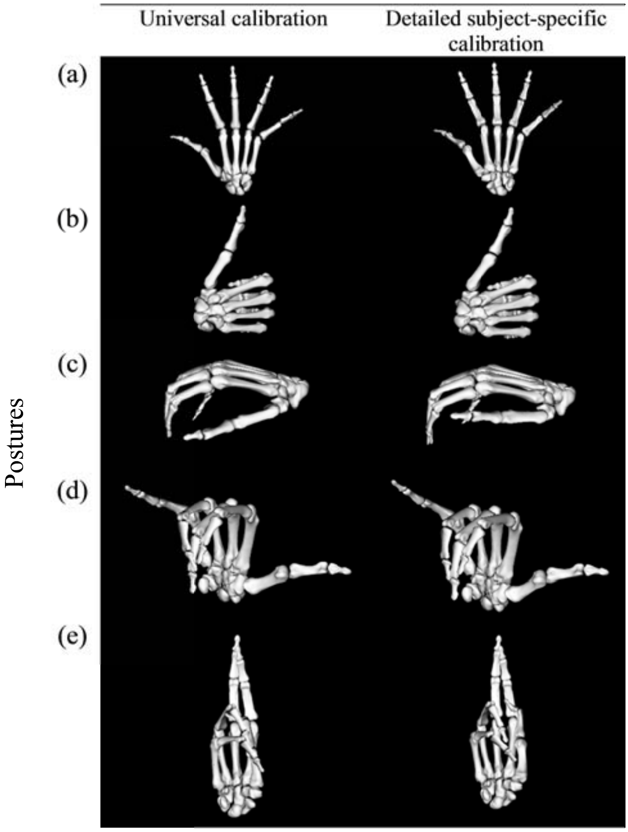
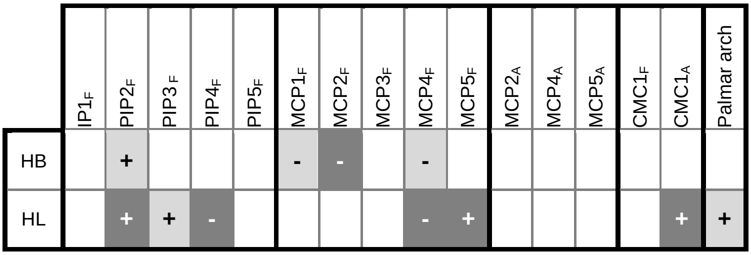


Figure 4.6. Pearson correlations of the precision errors with hand breadth (HB) and hand length (HL): darker shadowed cells for $p < 0.01$, lighter shadowed cells for $p < 0.05$. The sign of the correlations is also shown



	IP1$_F$	PIP2$_F$	PIP3$_F$	PIP4$_F$	PIP5$_F$	MCP1$_F$	MCP2$_F$	MCP3$_F$	MCP4$_F$	MCP5$_F$	MCP2$_A$	MCP4$_A$	MCP5$_A$	CMC1$_F$	CMC1$_A$	Palmar arch
HB		+				-	-		-							
HL		+	+	-					-	+					+	+

Phase 3. When the across-subject calibration protocol developed here was compared to a second "fast" calibration protocol, adapted from a previous method (Buffi et al. 2014), the mean precision errors from the across-subject calibration were approximately 3.3° smaller than those from the fast calibration (Table 4.3). More specifically, mean precision errors of IP and MCP joints from the across-subject calibration were smaller than those from the fast calibration. Highest bias and precision errors using the across-subject calibration corresponded to PIP5 flexion (-10.30º) and MCP5 flexion (13.45º), respectively. Highest bias and precision errors using the fast calibration correspond to MCP5 abduction (24.45º) and MCP3 flexion (22.46º), respectively.

Phase 4. AROM obtained for the pathologic subject were in accordance with the rehabilitation assessment performed by clinicians. The AROM were out of the normal range for CMC1 extension and abduction, IP1 flexion and extension, DIP2 to DIP5 flexion and extension, and in particular for MCP2 to MCP4 flexion the AROM was out of the range of the calibration (70°, 60° and 59° respectively, all of them lower than the 75° required). These limitations would disable the subject for performing the static postures of the Detailed calibration protocol, and obviously the cycles needed to account for the cross-coupling effect.

4.4 Discussion

The results of this work demonstrate promising approaches with strong potential to overcome critical problems associated with effective calibration of instrumented gloves. Such potential solutions are needed to advance technical capabilities for quantitative data collection during complex hand motions. First of all, we show that using a single, detailed calibration session for data collection from a single subject over multiple experimental sessions introduces only minimal error (mean precision error 3.50º), enabling data collection from the same subject over multiple days, without repeating a tedious, time-consuming calibration procedure. Furthermore, we propose that the small errors associated with using our across-subject calibration protocol (mean precision error 4.45º) are acceptable for many purposes. In addition to the reduction in time and effort associated with glove calibration, in the scenarios in which the error levels are permissible, this approach also has the potential to improve the accuracy with which hand kinematics can be quantified when the subject has a severe disability that interferes with the capacity to achieve subsets of hand postures essential for completion of the detailed, individualized calibration. Specifically, in this case, the results of our study suggest that the across-subject calibration would give better results than a detailed calibration in which some sensors could not be properly calibrated.

When comparing the difference between the joint angles that resulted when the same sensor outputs were transformed with both the across-subject calibration and the detailed subject-specific calibration, only three degrees of freedom (abduction of the little

MCP joint and flexion and abduction of CMC1 joint) yielded errors greater than 10º. Due to the complexity of the base joint of the thumb and the location of the sensors, it is not surprising that errors associated with CMC1 were relatively large. The larger error associated with abduction of the little finger can be explained because it represents an accumulated error. Specifically, flexion of little MCP joint is calculated as the sum of the relative abduction between little and ring fingers and the relative abduction between ring and middle fingers, yielding an accumulated error of a magnitude of approximately twice the error of similar joints.

Table 4.3. Mean values for bias and precision errors of using the across-subject calibration and the subject-specific fast calibration compared to using the videogrammetric technique

	Across-subject calibration			Subject-specific fast calibration		
Joint	Bias (º)	Precision (º)	Mean Precision of group of joints (º)	Bias (º)	Precision (º)	Mean Precision of group of joints (º)
IP1$_f$	-0.65	1.50	6.26	-2.20	9.13	9.13
PIP2$_f$	-3.09	5.56		-12.51	11.25	
PIP3$_f$	-4.86	9.40		-4.56	9.25	
PIP4$_f$	-3.77	4.68		-5.19	5.87	
PIP5$_f$	-10.30	10.19		-9.80	10.12	
MCP1$_f$	5.62	6.00	7.29	-4.66	2.20	13.32
MCP2$_f$	-2.28	6.64		8.31	13.20	
MCP3$_f$	-0.60	8.20		14.78	22.46	
MCP4$_f$	-9.87	2.17		5.34	16.93	
MCP5$_f$	7.92	13.45		3.95	11.83	
MCP2$_a$	1.76	7.26	8.08	1.19	10.29	11.47
MCP4$_a$	-0.05	8.18		5.68	10.00	
MCP5$_a$	4.01	8.80		24.45	14.11	
CMC1$_f$	-3.63	5.76		6.62	7.43	
CMC1$_a$	-1.73	6.81		-4.70	3.18	
Palmar arch	-0.41	8.69		-2.71	7.66	
Grand Mean	-1.37	7.08		1.50	10.31	

The results of our correlation analysis suggest that, when using the across-subject calibration, several joint angles are sensitive to hand size. This result is consistent with the motivation of a previous study that used hand segment lengths as an input to ANN as an algorithm to transform sensor output to joint angles (Zhou et al. 2010); although the success of this previous technique was not evaluated in terms of joint angle errors. We observed less sensitivity to hand breadth than hand length (e.g., only 4 degrees of freedom yielded significant correlations with hand breadth vs. 7 with hand length, Fig. 5). For MCP flexion, we note that 3 out of 5 MCP joints were negatively correlated to either hand length or breadth. Thus, using the across-subject calibration instead of using the detailed calibration generally yielded greater MCP flexion angles for smaller hands and smaller MCP flexion angles for larger hands. Overall, our correlation analysis suggests that the degree of variability in hand sizes across a group of subjects should be considered when implementing the across-subject calibration approach, especially if the application requires data of high precision.

When a single subject adopted five static postures and the joint angles estimated using the across-subject calibration were compared to the photogrammetric technique, we observed a small, negative bias error across all joints (e.g., on average, the joint angles were smaller for the across-subject data). In contrast, we note a small, positive bias error for the fast calibration. While our interpretation is limited by the fact that the videogrammetric data had to be taken separately, we postulate that the result of a negative bias (e.g., smaller joint excursions from the neutral posture) is consistent with the fact that the individuals were wearing a glove, increasing joint stiffness. In addition, another source of bias in the across-subject approach is that abduction angles of fingers were obtained assuming no abduction for the middle finger, which may affect the recorded values for the other abduction angles.

Given the benefits of instrumented gloves for quantification of complex hand movements discussed previously, our analysis suggests that the across-subject calibration approach is a feasible methodology for many applications in which the measurement of joint angles is required (ranging from clinical diagnosis, rehabilitation or functional assessment, to robotics). Because we observed smaller differences relative to a reference data set (Table 4.3), we conclude the across-subject calibration methodology performed more effectively than the fast calibration protocol (grand mean precision errors 7.08° and 10.31°, respectively). While this analysis was completed with an 18-sensor Cyberglove, it is extendable to a 22-sensor Cyberglove, which registers also fingers distal IP joint flexion. In order to use it, an analogous procedure to that presented for the rest of IP joints could be used.

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This article has no relevant Conflict of Interests.

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Chapter
05

FUNCTIONAL RANGE OF MOTION OF THE HAND JOINTS IN ACTIVITIES OF THE INTERNATIONAL CLASSIFICATION OF FUNCTIONING, DISABILITY AND HEALTH (ICF)

ABSTRACT, KEY TERMS & ABBREVIATIONS

Abstract

Study Design: Cross-sectional research design

Introduction: The active range of motion (AROM) is commonly used as an index of hand function recovery after injury. However, functional range of motion (FROM) data in the literature, compared with AROM, is scarce, limited to flexions, and fail to represent activities of daily living (ADL).

Purpose of the Study: To provide FROM of the dominant hand joints in ADL, including flexions, abductions and palmar arching, in order to establish a relationship between AROM and hand function in people less than 50 years.

Methods: AROM of hand joints and hand postures in 24 representative ADL according to the ICF were recorded in 24 subjects (12 men, 12 women). A thorough descriptive analysis of the hand postures and comparison with AROM values were performed.

Results: Detailed quantitative FROM data are reported globally, per activity and ICF area, and compared with AROM values. Global AROM and FROM dependency with gender and hand size is also reported.

Discussion: AROM values are consistent with those in the literature, but more complete. Median values of hand postures should serve for decision-making in clinical interventions. In general, the FROM values required to perform ADL are much lower than the AROM values, from 5º to 28º depending on the movement and joint, with the exception of palmar arch and some thumb and little finger joints.

Conclusions: The data reported are clinically relevant to assess hand functionality.

Level of Evidence: N/A

Key terms

Hand joints, functional range of motion, active range of motion.

Abbreviations:

ADL: activities of daily living
ADL_FROM: specific FROM for each ADL
AROM: active range of motion
CMC: carpometacarpal

Ch_Postures: hand postures from all subjects in all ADLs of each ICF chapter
FROM: functional range of motion
G_AROM: global AROM
G_FROM: global FROM
G_Postures: hand postures from all subjects in all ADLs
ICF International Classification of Functioning, Disability and Health
IP: interphalangeal
MCP: metacarpophalangeal
PIP: proximal interphalangeal
PROM: passive range of motion
ROM: range of motion
s_AROM: subject-specific AROM
s_FROM: subject-specific FROM
WHO: World Health Organization

5.1 Introduction

Hand therapists use different intervention strategies to restore the range of motion (ROM) of hand joints after hand injury and surgery (Michlovitz et al. 2004). The ultimate goal is to reduce impairments and enhance functional performance for activities of daily living (ADL) as well as work and leisure activities. During the rehabilitation processes, therapists assess the active and passive ROM (AROM and PROM, respectively) of hand joints as general indicators of the hand function (Clarkson 2012; Lee & Jung 2015).

More recently, the assessment of the functional range of motion (FROM) has been proposed, especially for the wrist, elbow and shoulder. The FROM is defined as the minimum ROM necessary to comfortably and effectively perform ADL (Vasen et al. 1995). The FROM in the wrist, elbow and shoulder required for ADL has been reported to be less than the AROM (Ryu et al. 1991; Sardelli et al. 2011; Namdari et al. 2012). These data are relevant, as they can be used to dictate clinical care and assess outcomes. Very few works have addressed the establishment of the FROM of the thumb and finger joints (Hume et al. 1990; Hayashi & Shimizu 2013; Bain et al. 2014; Coupier et al. 2015): Hume et al. (Hume et al. 1990) studied flexion of the metacarpophalangeal (MCP) and interphalangeal (IP) joints of the thumb and fingers; Hayashi et al. (Hayashi & Shimizu 2013) studied flexion of the MCP joints of fingers; and the most recent work by Bain et al. (Bain et al. 2014) studied flexion of the MCP and IP joints of fingers. The results of FROM reported in these works seem to be aligned with those reported for the wrist, elbow and shoulder, with lower values of FROM than AROM. However, there is no consensus concerning the computation of the FROM. Many works have used the average of the extreme values across subjects recorded during the development of a set of activities (Hume et al. 1990; Hayashi & Shimizu 2013). This is recognized in Bain et al. (Bain et al. 2014) to provide excessive values, therefore proposing the use of the extreme values of 90% of the activities considered. In other works, the median and 5th and 95th percentiles of the postures used are provided to analyze the requirements for upper extremity motions during activities of daily living (Aizawa et al. 2010; Magermans et al. 2005). In addition, the available studies on FROM of hand joints present some deficiencies and limitations. The first deficiency is that none of them analyzes the palmar arching provided by the flexion of the little and ring carpometacarpal (CMC) joints nor the abduction motions of the fingers or thumb, as was also observed in a recent review work (Lee & Jung 2015), where attention was drawn to the need for further research examining the ROM and hand functions of the thumb, because of its importance in hand function (Li & Tang 2007). Abductions of fingers are needed to assure stability when grasping objects with different sizes, as they allow for higher distances between fingertips. And thumb abduction, along with palmar arching, are fundamental in many ADL to perform thumb opposition to fingertips.

Another limitation arises from the way the FROM was measured. The works by Hume et al. (Hume et al. 1990) and Bain et al. (Bain et al. 2014) both measured only one static position for each activity, which was hypothesized to be representative of the whole activity, thus losing many joint angle data, e.g., maximum hand opening is achieved about midway through the reaching movement (Santello & Soechting 1998). Only the work by Hayashi et al. (Hayashi & Shimizu 2013) took into account all the postures adopted during the activities performed.

An additional limitation comes from the selection of the tasks representing the ADL: Hume et al. (Hume et al. 1990) used 11 varied activities chosen with no systematic criterion, Hayashi et al. (Hayashi & Shimizu 2013) used 19 activities from the DASH test, and Bain et al. (Bain et al. 2014) used the 20 activities from the Sollerman hand grip function test. An appropriate selection of activities representing the ADL is very important to obtain clinically relevant data and to avoid misleading conclusions. Assessment tests like the DASH or Sollerman hand grip function tests were developed for specific illnesses so that their use for assessing the hand function for other pathologies is limited. In particular, the activities of the DASH test are focused on assessing the function of the arm as a whole instead of the specific hand function, and the Sollerman hand grip function test, although being focused on assessing the hand function, lacks activities representing some important ADL aspects, as doing housework. In this sense, the International Classification of Functioning, Disability and Health (ICF)(WHO 2001) is the framework of the World Health Organization (WHO) for measuring health and disability at both individual and population levels. The ICF is, therefore, a standardized and accepted reference for reporting the level of functional recovery. To this end, the ADL are systematically collected in the "Activities and Participation" component of the "Functioning and Disability" part of the ICF.

Consequently, the purpose of the current study was to analyze the FROM of the thumb and finger joints of the right hand in people under 50 years for carrying out a reduced set of representative ADL of the ICF, including abduction motion and palmar arching, unlike other approaches. Also, the goodness of assessing hand functionality directly through AROM (as hand therapists usually do) is investigated through the comparison between FROM and AROM values.

5.2 Material and methods

The experiment was approved by the University Ethical Committee, in accordance with the Declaration of the World Medical Association. Twenty-four right-handed subjects (12 males and 12 females) participated in the experiment, whose descriptive data are shown in Table 5.1. All the participants, free of hand lesions or pathologies, were properly informed and gave their written consent. The age was intentionally lower than 50 years to avoid kinematic alterations due to joint degeneration caused by the process of aging.

Table 5.1. Descriptive data of the subjects participating in the experiment. HL: hand length (from the proximal palmar crease to the tip of the middle finger), HW: hand width (at the metacarpal heads, including thumb)

		Age (years)	HL (mm)	HW (mm)
Men	Mean (SD)	33.3 (9.7)	194.8 (7.1)	103.8 (5.8)
	Min	20.0	178.0	92.0
	Max	46.0	205.0	110.0
Women	Mean (SD)	34.3 (8.2)	178.4 (9.2)	90.4 (4.9)
	Min	21.0	158.0	82.0
	Max	46.0	189.0	97.0

5.2.1 AROM and FROM assessment

A right-hand instrumented glove (Cyberglove Systems LLC; San Jose, CA), equipped with 18 resistive bend sensors, was used to measure the hand posture. A previously validated protocol was used to obtain 16 hand joint angles from the data from the sensors, with a global precision error of 4.45º (Gracia-Ibáñez et al. 2016): flexion at all fingers and thumb joints (thumb CMC joint, MCP joint of thumb and fingers, proximal IP (PIP) joints of fingers and IP joint of thumb); abduction between thumb and index finger due to CMC joint of the thumb; abductions at MCP joints between index and middle, middle and ring, and ring and little fingers; and finally, flexion of palmar arch. Flexion was considered as the motion in the sagittal plane of each finger or thumb, in volar direction; thumb CMC abduction, as the motion in the plane perpendicular to the palm, which separates the thumb from the palm in palmar direction; index-middle, middle-ring and ring-little abductions, as the motions in the palmar plane that separate one finger from each other; and flexion of palmar arch, as the angle described in Figure 5.1. The protocol uses *across-subject gains* to transform the sensor data into joint angles, and requires the recording of a reference posture for each subject (Figure 5.2), in which all joint angles are considered as 0º. Flexion and abduction angles from this reference posture were considered positive, while extension and adduction angles from the reference posture were considered negative.

Figure 5.1. Definition of the palmar arching measured by the glove protocol, and examples of postures with different palmar arching values

Figure 5.2. Reference posture in which all joint angles are considered as zero: the hand is resting flat on a table, with the fingers and thumb close together

The AROM of the hand joints of each subject was assessed by measuring ten actively forced static postures (Figure 5.3), AROM postures, selected according to the indications of Clarkson (Clarkson 2012), in order to have maximum values for: flexion and extension of all fingers and thumb joints, abductions of MCP joints of fingers and thumb CMC joint, and flexion of palmar arch. For adductions, and for extension of palmar arch, AROM values were considered as 0º.

The FROM of the hand joints was evaluated for each subject by recording the hand posture while performing a set of ADL selected to cover all the areas of the ICF Chapters most directly related with hand function (Table 5.2), although lacking from exhaustiveness for two reasons: the restriction of defining a limited, feasible set of ADL and the limitations arising from the use of an instrumented glove for specific activities, such as '*d6506 Taking care of animals*'.

Figure 5.3. Static postures used to determine the AROM of the hand joints: (a) Thumb CMC maximal flexion; (b) Thumb CMC, MCP and IP maximal extension; (c) Thumb CMC maximal abduction; (d) Fingers PIP and thumb IP and MCP maximal flexion; (e) Fingers MCP maximal flexion, achieved when trying to touch the base of the palm with the fingertips; (f) Fingers, except thumb, PIP and MCP maximal extension; (g1) to (g3) Index, ring and little fingers maximal abduction, respectively; (h) Maximal palmar arching

5.2.2 Experimental procedure and analysis

For each subject, the reference posture (static trial) was recorded (Figure 5.2), and considered as 0° for all joints. Then, 10 AROM postures (static trials) were recorded for each subject, and the hand joint angles at the joints of interest were calculated using the glove protocol (Gracia-Ibáñez et al. 2016) (the mean value of the sensor data during each static trial was considered), thus obtaining the subject-specific AROM (s_AROM) for the different joints and movements. Statistical values across subjects of these s_AROM values were calculated, both globally and stratified by gender, and the resulting mean values were used as global AROM (G_AROM) at each joint. Statistical differences in AROM between genders were checked by means of a set of ANOVAs (27 analyzes, one per each AROM measured): dependent variable 's_AROM', with factor 'gender'. Dependency of AROM values on hand size was checked through Pearson's correlation coefficients between hand length and s_AROM, for each AROM measured.

Table 5.2. ADL selected for defining the FROM of the hand joints, body posture used, and corresponding ICF Chapter and Area.

ICF Chapter	ICF area	ADL selected	Body posture
3. Communication	d325. Communicating with - receiving - written messages	1. Reading	Seated
	d345. Writing messages	2. Writing	Seated
	d360. Using communication devices and techniques	3. Talking by phone	Seated
		4. Typing numbers on the phone	Seated
		5. Typing on PC keyboard	Seated
4. Mobility	d430. Lifting and carrying objects	6. Handling a book	Standing
	d440. Fine hand use	7. Using a key to open a door	Standing
	d445. Hand and arm use	8. Opening a door	Standing
5. Self-care	d520. Caring for body parts	9. Turning on and off the faucet	Standing
		10. Washing and drying hands	Standing
		11. Brushing teeth	Standing
		12. Putting toothpaste onto a toothbrush	Standing
		13. Combing hair	Standing
	d540. Dressing	14. Putting on a shirt and fastening two buttons	Standing
		15. Putting on pants, buttoning and zipping them up	Standing
		16. Putting on a shoe and tying the shoelaces	Seated
	d550. Eating	17. Eating soup	Seated
		18. Cutting with a knife	Seated
		19. Eating with a fork	Seated
	d560. Drinking	20. Pouring water	Seated
		21. Drinking water	Seated
6. Domestic life	d640. Doing housework	22. Using a spray	Standing
		23. Cleaning using a cloth	Standing
		24. Ironing	Standing

Subsequently, in order to evaluate the FROM, 24 dynamic trials were recorded for each subject, one for each of the 24 ADL selected. The objects used in these ADL were placed in the same starting position for all the subjects, and they started and finished each activity with the same hand posture: for standing up activities, with the arms and hands relaxed at their sides; for seated activities, with the palm of the hand lying relaxed on the table. All the ADL were performed in laboratory conditions, with the same instructions for all the subjects, and using real objects. Placement of objects and subjects was controlled, as well as the actions and their sequencing to accomplish each ADL. As an example, for the action of serving water, the subject was sat in front of a table, with the hands lying on the table at shoulders distance, and the position of the bottle and the glass was the same for all the subjects. At the operator's indication, the subject took the bottle, served half a glass of water, released the bottle to its original position and returned the hands to the starting position lying on the table. The glove sensor data were recorded with a sampling frequency of 75 Hz, resulting in a sequence of hand postures that could be assimilated to frames as in a video recording. For each trial and frame, the joint angles in each hand posture were obtained with the same protocol. The beginning and end of each trial was trimmed by removing the frames in which all the joint angles varied by less than 2.5% from the initial or end posture, respectively, to avoid a starting/ending hand posture bias. The remaining frames of each trial were filtered with a 2nd order, 2-way Butterworth filter with cutoff frequency of 5 Hz to avoid noise due to artifacts. The number of frames per trial after trimming varied from 259 to 2461. A total of 576 dynamic trials resulted from all the ADL (24) and subjects (24), consisting of more than 621,100 frames, with angles for 16 hand joints in each frame. These data represent the hand postures used by the subjects when performing the 24 ADL. For each subject, a subject-specific FROM (s_FROM) for each hand joint angle was calculated as the 5th and 95th percentiles of all his/her frames, therefore representing the range of angles covering 90% of the postures used by each subject during all the ADL. Statistical values across subjects of these s_FROM data were calculated, both globally and stratified by gender, and the resulting mean values were used as global FROM (G_FROM) at each joint. Statistical differences in FROM between genders were checked by means of a set of ANOVAs (32 analyzes, two per each movement measured): dependent variable 's_FROM', with factor 'gender'. Dependency of FROM values on hand size was checked through Pearson's correlation coefficients between hand length and s_FROM, for each FROM measured.

In order to compare AROM with FROM, a paired t-test was performed for each of the 32 movements to check statistical differences between s_AROM and s_FROM (s_AROM was considered 0º for all those joint movements where the AROM was not measured).

Furthermore, a specific FROM for each ADL (ADL_FROM) at each joint angle was defined by the 5th and 95th percentiles of the joint angles of the frames of all the subjects for the ADL considered, therefore representing the range of angles covering 90% of the postures used during each ADL at each specific joint by all the subjects of the sample.

Additionally, the requirements for hand postures during ADL were graphically analyzed, both globally and per ICF chapter. For each hand joint angle, and considering the data from all the frames and subjects, descriptive statistics were computed (median, extreme values and 5th, 25th, 75th and 95th percentiles) as global estimates of the distribution of the hand postures used to perform all the ADL considered for all the subjects of the sample (G_Postures). The same analysis was performed stratified by ICF Chapter (Ch_Postures). These statistics of G_Postures and Ch_Postures were represented with box-plots, accompanied by the G_AROM values measured, represented with bars, for their comparison.

In order to consider a subject specific comparison between AROM and FROM, an additional analysis was performed to deepen knowledge about the goodness of the assessment of hand functionality directly with AROM. For each subject, each joint angle was linearly re-scaled so that values 0 and 100 correspond to the lower and upper bounds of the s_AROM. With this normalization, the new data is a measure of the deviation of the recorded angle with respect to each s_AROM, thereby allowing comparison between values from different subjects. Histograms of re-scaled angles from all frames (time instants) were plotted for each hand joint. Also, for each ADL, the percentages of time beneath re-scaled values of 0, 10, 20 and 30, and over 70, 80, 90 and 100 were computed.

5.3 Results

Mean and standard deviation (SD) values of s_AROM both globally and stratified by gender are shown in Table 5.3. Significant differences in s_AROM values between genders from the ANOVAs are marked in this table with *, and significant correlations of s_AROM values with hand size are marked with $ (preceded by the sign of the correlation, + or –). The mean values at each joint are considered as G_AROM. As expected, the highest s_AROM values correspond to the flexion/extension of IP and PIP joints, followed by finger flexion/extension at MCP joints, while the lowest s_AROM values are found for abduction/adduction. In general, the s_AROM values are not affected by gender or hand size.

Mean and standard deviation (SD) values of s_FROM both globally and stratified by gender are shown in Table 5.4. Again, significant differences in s_FROM values between genders from the ANOVAs are marked in this table with *, and significant correlations of s_FROM values with hand size are marked with $ (preceded by the sign of the correlation, + or –). The mean values at each joint are considered as G_FROM. This table can be used to check the levels of G_FROM needed to globally perform the ADL considered. The G_FROM values are more affected by gender than the G_AROM values, seemingly due to differences in hand sizes. Especially MCP joints and palmar arch are the most dependent joints, as bigger hands need more flexed postures to grasp the same objects.

Table 5.3. Global AROM (G_AROM), globally and stratified by gender: mean and standard deviation (SD) values of subject specific AROM (s_AROM) values across subjects, mean values being considered as G_AROM. Note that no adduction AROM was registered at finger MCP joints and the thumb CMC joint, nor extension AROM at the palmar arch. Significant differences by gender from ANOVAs: * $p < 0.05$, ** $p < 0.01$. Significant Pearson's correlations with hand length: $^{\$}$ $p < 0.05$, $^{\$\$}$ $p < 0.01$, the signs + /– denote the sign of the correlation.

Digit	Joint	Motion	Mean (SD) s_AROM (º) lower bound / upper bound		
			Global	Men	Women
Thumb	CMC	Flexion	-26.2 / 42.1 (16.8) / (10.3)	-28.9 / 42.3 (15.5) / (12.4)	-23.5 / 41.9 (18.2) / (8.3)
	MCP	Flexion	-21.0 / 26.1 (11.7) / (9.1)	-23.3 / 24.6 (8.7) / (10.2)	-18.6 / 27.6 (14.1) / (7.9)
	IP	Flexion	-12.4 / 102.1 (14.6) / (19.7)	-15.7 / 108.9 (15.3) / (17.7)	-9.0 / 95.3 (13.7) / (20.0)
Thumb-Index	CMC	Abduction	0.0 / 19.7 (0.0) / (3.7)	0.0 / 20.7 (0.0) / (3.7)	0.0 / 18.8 (0.0) / (3.7)
Index	MCP	Flexion	-25.3 / $70.6^{+\$\$}$ (14.5) / (9.1)	-30.2 / 72.2 (15.3) / (7.5)	-20.4 / 69.0 (12.4) / (10.6)
	PIP	Flexion	-3.8 / 108.8 (4.0) / (9.1)	-2.9 / 109.7 (3.1) / (9.4)	-4.7 / 107.8 (4.9) / (9.1)
Index-Middle	MCP	Abduction	0.0 / 35.2 (0.0) / (6.3)	0.0 / 37.0 (0.0) / (6.0)	0.0 / 33.4 (0.0) / (6.4)
Middle	MCP	Flexion	-27.9 / $81.9^{+\$}$ (14.4) / (11.2)	-27.7 / 83.2 (15.9) / (9.8)	-28.2 / 80.6 (13.6) / (12.7)
	PIP	Flexion	-6.7 / 96.6 (4.9) / (9.6)	-7.2 / 97.1 (4.8) / (9.8)	-6.2 / 96.1 (5.3) / (9.7)
Middle-Ring	MCP	Abduction	0.0 / 25.7 (0.0) / (5.6)	0.0 / 28.8 (0.0) / (5.4)	0.0 / 22.6 (0.0) / (4.1)
Ring	MCP	Flexion	-23.1 / $73.6^{+\$}$ (11.1) / (8.9)	-21.1 / 75.8* (9.6) / (6.5)	-25.1 / 71.4* (12.7) / (10.7)
	PIP	Flexion	-9.9 / 102.8 (6.5) / (7.6)	-10.9 / 102.4 (7.7) / (8.8)	-8.9 / 103.1 (5.4) / (6.4)
Ring-Little	MCP	Abduction	0.0 / 28.4 (0.0) / (3.8)	0.0 / 29.2 (0.0) / (4.3)	0.0 / 27.5 (0.0) / (3.2)
Little	MCP	Flexion	-21.9 / 68.4 (12.1) / (7.0)	-21.1 / 67.7 (10.4) / (6.0)	-22.7 / 69.2 (14.2) / (8.1)
	PIP	Flexion	-7.8 / 89.9 (8.1) / (10.1)	-8.1 / 89.3 (10.0) / (12.3)	-7.5 / 90.5 (6.3) / (7.9)
Palm	Palmar arch	Flexion	0.0 / 29.6 (0.0) / (8.6)	0.0 / 35.8** (0.0) / (5.8)	0.0 / 23.5** (0.0) / (6.1)

Table 5.4. Global FROM (G_FROM), globally and stratified by gender: mean and standard deviation (SD) values of subject specific FROM (s_FROM) values across subjects, mean values being considered as G_FROM. Significant differences by gender from ANOVAs: * p <0.05, ** p<0.01. Significant Pearson's correlations with hand length: $^{\$}$ p <0.05, $^{\$\$}$ p<0.01, the signs + /– denote the sign of the correlation.

Digit	Joint	Motion	Mean (SD) s_FROM (º) lower bound / upper bound		
			Global	Men	Women
Thumb	CMC	Flexion	-11.2 / 33.9 (12.8) / (10.4)	-7.4 / 34.8 (11.5) / (12.2)	-15.0 / 33.0 (13.4) / (8.7)
	MCP	Flexion	-17.1 / 14.3 (6.8) / (7.8)	-19.1 / 11.5 (4.5) / (6.8)	-15.2 / 17.1 (8.2) / (8.0)
	IP	Flexion	-7.2 / 80.6 (14.5) / (23.4)	-4.7 / 82.5 (12.8) / (21.7)	-9.7 / 78.7 (16.2) / (25.8)
Thumb-Index	CMC	Abduction	5.4 / 21.2 (2.6) / (4.0)	6.1/ 22.2 (2.7) / (4.6)	4.7 / 20.2 (2.4) / (3.2)
Index	MCP	Flexion	$-1.8^{+\$\$}$ / $51.5^{+\$}$ (10.2) / (9.8)	2.7* / 52.5 (6.6) / (6.6)	-6.3* / 50.6 (11.4) / (12.5)
	PIP	Flexion	4.6 / $88.9^{+\$}$ (7.1) / (13.6)	5.6 / 86.1 (7.6) / (12.3)	-3.5 / 75.6 (6.8) / (13.2)
Index-Middle	MCP	Abduction	-7.3 / $16.0^{-\$}$ (2.8) / (3.4)	-7.6 / 14.3** (2.5) / (2.2)	-7.0 / 17.8** (3.1) / (3.6)
Middle	MCP	Flexion	$-1.3^{+\$\$}$ / $62.7^{+\$\$}$ (10.1) / (13.5)	5.2** / 65.5 (6.3) / (9.7)	-7.8** / 59.9 (9.0) / (16.4)
	PIP	Flexion	8.3 / 78.3 (4.6) / (7.6)	9.9 / 78.1 (4.9) / (4.8)	6.7 / 78.5 (3.8) / (9.8)
Middle-Ring	MCP	Abduction	-13.7 / 2.2 (3.0) / (3.5)	-13.0 / 2.0 (2.5) / (4.2)	-14.4 / 2.4 (3.3) / (2.8)
Ring	MCP	Flexion	$-5.5^{+\$\$}$ / $60.8^{+\$\$}$ (6.6) / (11.5)	-2.2* / 64.9 (5.1) / (7.0)	-8.7* / 56.7 (6.4) / (13.7)
	PIP	Flexion	9.3 / 91.1 (5.9) / (7.8)	11.6 / 90.3 (6.4) / (6.7)	7.0 / 92.0 (4.4) / (9.1)
Ring-Little	MCP	Abduction	-8.1 / $10.6^{-\$}$ (3.1) / (4.4)	-7.4 / 8.8* (2.5) / (3.8)	-8.8 / 12.4* (3.6) / (4.3)
Little	MCP	Flexion	-5.4 / 71.0 (6.0) / (8.2)	-4.5 / 71.6 (4.8) / (5.8)	-6.4 / 70.4 (7.1) / (10.3)
	PIP	Flexion	6.6 / $84.5^{-\$}$ (6.4) / (9.8)	10.4** / 81.2 (6.4) / (7.1)	2.9** / 87.8 (3.9) / (11.2)
Palm	Palmar arch	Flexion	$-5.2^{+\$\$}$ / 29.8 (8.5) / (9.7)	-0.2** / 33.9* (7.8) / (10.1)	-10.2** / 25.8* (5.9) / (7.6)

All measured G_AROM values are higher than G_FROM, except for flexion of the MCP joint of the little finger and the palmar arch, and the thumb-index CMC abduction, which have slightly higher values of G_FROM. These differences can be analyzed in more detail by means of the results of the paired t-test shown in Table 5.5, which compares differences between subject specific ROM values (s_AROM and s_FROM). No statistically significant differences have been found between measured s_AROM and s_FROM values for extension of MCP and IP joints of the thumb and for flexion of the MCP joint of the little finger and the palmar arch. Measured s_AROM values are significantly higher ($p<0.05$) than s_FROM values for most hand joint motions. Highest differences between s_AROM and s_FROM values correspond to flexion of the IP joint of the thumb and the PIP joint of the index finger, extension of MCP joints of the index and middle fingers, and to abduction between fingers. But s_AROM of many other hand joint motions exceed s_FROM in more than 10 degrees. Only for abduction at the thumb CMC joint a significantly higher value of s_FROM than s_AROM has been found, although with a very small difference.

Table 5.5. Results of the paired t-tests: mean values of the differences s_FROM – s_AROM and p-values of the tests.

Digit	Joint	Motion	lower bound _s_FROM – lower bound _s_AROM		upper bound _s_FROM – upper bound _s_AROM	
			Mean difference	P value (2-tailed)	Mean difference	P value (2-tailed)
Thumb	CMC	Flexion	14.9	0.001	-8.2	0.000
	MCP	Flexion	3.8	0.137	-11.8	0.000
	IP	Flexion	5.2	0.181	-21.6	0.000
Thumb-Index	CMC	Abduction	5.4*	0.000	1.5	0.005
Index	MCP	Flexion	23.7	0.000	-19.0	0.000
	PIP	Flexion	8.5	0.001	-27.9	0.000
Index-Middle	MCP	Abduction	-7.3*	0.000	-18.5	0.000
Middle	MCP	Flexion	28.5	0.000	-19.2	0.000
	PIP	Flexion	15.5	0.000	-18.3	0.000
Middle-Ring	MCP	Abduction	-13.4*	0.000	-23.2	0.000
Ring	MCP	Flexion	18.7	0.000	-12.8	0.000
	PIP	Flexion	19.9	0.000	-11.6	0.000
Ring-Little	MCP	Abduction	-7.7*	0.000	-17.3	0.000
Little	MCP	Flexion	16.8	0.000	2.6	0.107
	PIP	Flexion	16.4	0.000	-5.4	0.014
Palm	Palmar arch	Flexion	-4.4*	0.059	-0.1	0.966

* AROM has not been measured for these movements

ADL_FROM values obtained are presented in Table 5.6. This table can be used to check the level of FROM needed to perform each specific ADL, which are very different between ADLs, as it is clearly observed in the table.

Table 5.6. FROM for each ADL: 5th / 95th percentiles of each hand joint angle from the frames of all the subjects for each ADL (ADL_FROM).

		Thumb			Thumb-Index	Index		Index-Middle	Middle		Middle-Ring	Ring		Ring-Little	Little		Palm
		CMC Flex (º)	MCP Flex (º)	IP Flex (º)	CMC Abd (º)	MCP Flex (º)	PIP Flex (º)	MCP Abd (º)	MCP Flex (º)	PIP Flex (º)	MCP Abd (º)	MCP Flex (º)	PIP Flex (º)	MCP Abd (º)	MCP Flex (º)	PIP Flex (º)	Arch Flex (º)
Activities	1	-22/32	-19/10	-17/59	2/20	-4/41	3/57	-4/11	-8/51	-1/48	-12/0	-8/40	0/53	-8/4	-8/44	0/43	-1/27
	2	-13/41	-21/14	-12/118	10/25	5/57	20/103	-5/18	0/68	10/82	-18/-1	3/65	37/99	-3/14	12/82	22/90	4/44
	3	-32/23	-25/9	-1/83	2/17	-29/31	-1/90	-3/32	-24/54	8/89	-18/2	-10/59	8/94	-6/13	-3/73	6/87	-8/25
	4	-26/18	-18/27	7/72	1/16	-3/45	-2/41	-4/15	-11/66	3/81	-15/-1	-12/47	3/88	-11/4	-12/46	2/74	-7/30
	5	-22/25	-15/10	6/61	2/17	-5/36	12/62	-2/14	-15/35	9/65	-16/-3	-20/17	10/67	-14/0	-20/16	2/40	-4/31
	6	-21/35	-14/17	0/61	7/21	-10/49	3/57	-8/13	-5/66	-1/59	-11/7	-3/67	-2/63	-5/10	3/72	-14/44	2/37
	7	-36/20	-19/31	9/98	5/22	3/78	18/108	-12/9	0/85	15/90	-11/3	-3/69	15/92	-9/7	-7/65	6/76	-18/29
	8	-13/38	-13/14	-8/69	4/24	3/62	7/84	-13/7	9/79	11/71	-10/5	2/66	11/75	-6/10	1/72	12/65	-3/34
	9	-22/23	-27/13	11/90	4/24	-16/48	7/88	-15/16	1/74	17/75	-9/12	5/76	21/96	-3/14	7/81	15/88	-7/35
	10	-32/32	-17/14	5/61	0/18	-10/52	-1/72	-9/12	-14/59	3/71	-13/5	-10/53	4/78	-8/10	-7/63	-2/66	-3/29
	11	-18/41	-10/20	-25/51	5/20	1/59	6/74	-10/14	-2/66	17/86	-13/2	-2/62	22/100	-9/14	-10/78	17/97	-16/27
	12	-15/43	-15/13	-25/57	4/21	2/53	7/83	-9/13	-3/59	16/78	-13/2	-4/58	22/87	-7/12	-3/70	15/89	-9/32
	13	-17/46	-13/17	-25/51	3/20	-13/48	3/81	-4/19	-8/66	18/79	-14/3	-3/64	18/87	-5/14	3/74	11/77	-9/32
	14	-8/45	-13/15	-18/59	6/23	1/55	13/73	-7/13	-1/62	13/74	-12/2	-1/56	17/79	-8/9	-1/65	6/73	-7/29
	15	-13/41	-16/20	-30/80	5/22	-1/59	12/90	-12/16	-2/65	15/89	-13/7	1/61	15/93	-8/11	2/68	7/84	-9/31
	16	-13/45	-14/17	-24/70	5/22	-1/54	5/78	-12/13	-7/59	8/84	-13/6	-4/56	12/95	-8/11	-3/63	8/84	-6/33
	17	-14/40	-10/21	4/86	5/18	0/55	14/80	-11/11	1/72	21/71	-10/4	7/64	27/94	-3/13	6/75	22/85	-7/43
	18	-2/45	-6/24	0/77	6/19	11/57	-9/58	-6/15	6/74	39/79	-15/1	8/73	48/100	-2/16	11/79	33/101	-14/25
	19	-10/38	-7/26	-12/58	4/18	15/57	-5/81	-8/11	2/69	27/79	-15/3	6/61	35/99	-3/17	7/76	27/102	-19/27
	20	-9/40	-29/3	8/84	5/26	-20/25	12/64	2/24	-14/46	8/54	-15/-1	-8/44	6/59	-11/6	-6/50	-3/47	-2/36
	21	-12/38	-24/4	8/94	6/26	-28/27	13/68	-1/17	-12/44	9/48	-20/-2	-13/36	5/55	-13/8	-5/56	-3/51	-3/35
	22	-25/41	-19/14	1/70	7/22	-7/45	11/76	-5/13	-10/57	13/66	-13/5	-5/61	15/79	-7/10	-1/70	9/66	-5/29
	23	-16/39	-14/16	-3/57	1/17	-7/41	-3/65	-5/21	-18/38	-1/79	-21/-2	-27/35	0/92	-18/4	-28/41	-3/94	-12/26
	24	-26/32	-25/14	-11/63	7/23	-1/60	21/89	-2/23	5/77	23/75	-14/2	3/75	24/74	-5/16	4/80	16/62	-14/27

The distributions of G_Postures and Ch_Postures for each hand joint are shown in Figure 5.4, along with G_AROM values. The distribution of G_Postures and Ch_Postures is represented through whiskers for extreme values (minimum and maximum), boxes for percentiles (5th, 25th, 75th and 95th percentiles) and an inner line for the median. The G_AROM values measured are represented with bars. This figure can be used to check the level of FROM required for the set of representative activities considered in each chapter. Median values and percentiles of Ch_Postures present some differences among chapters, and with those of G_Postures, especially for flexion of the thumb CMC joint, along with flexion of finger MCP and PIP joints. Note that G_AROM values are lower than the extreme G_Postures values for all hand joints, although they contain 90% of the G_Postures for most hand joint motions, as explained above. Note also that G_AROM of abduction of MCP joints of fingers do not seem to contain 90% of the G_Postures. However, maximal angles of these joints were recorded only in the sense of abducting the fingers, so that this comparison is hampered by a lack of information in the sense of adducting. The same argument applies to the palmar arching, where the maximal extension was not recorded. Furthermore, as previously noted, these comparisons have to be taken with caution, as subject-specific values are being compared with mean AROM values across subjects.

Histograms of re-scaled angles from all the frames (time instants) are presented in Figure 5.5, along with the percentages of time beyond the s_AROM values. These histograms can be used to check the percentage of time that each re-scaled angle is used. In those cases where both s_AROM values were measured, many distributions present a bell-shaped profile more or less centered within the s_AROM values, like some histograms of thumb and index joints. Nevertheless, other joints present a bimodal profile, e.g., flexion of MCP joints of ring and little fingers. Some of the bell-shaped distributions are somewhat skewed within the measured s_AROM values, especially flexion of the thumb IP joint. Some distributions have longer tails than others, e.g., extension of the thumb CMC and MCP joints, thus providing a higher percentage of time beyond the measured s_AROM values. The highest percentage of time beyond measured s_AROM corresponds to palmar deviation of the abduction of the CMC joint (more than 12% of time), followed by flexion of the MCP of the little finger (more than 11%).

A more detailed comparison of AROM and FROM values for each ADL is presented in the appendix. For each joint movement, the percentages of time beneath re-scaled angles of 0, 10, 20 and 30, and over 70, 80, 90 and 100 are presented. These tables can be used by clinicians to estimate the loss of functionality for performing each ADL of a person who has experienced a reduction of his/her AROM because of a lesion or pathology (an example of use is provided in the next section).

Figure 5.4. Comparison between G_AROM and hand postures used, globally and stratified by chapter (G_Postures and Ch_Postures): representation of the descriptive statistics of the distributions of G_Postures, Ch_Postures and G_AROM values obtained for each hand joint angle for the representative activities considered. The whiskers represent extreme values; the thinnest boxes represent the 5th and 95th percentiles; the thickest boxes represent the 25th and 75th percentiles; and the inner line represents the median. G_AROM values represented with bars. (*) Note that no adduction AROM was registered at finger MCP joints and the thumb CMC joint, nor extension AROM at the palmar arch. Nomenclature: CMC (carpometacarpal), IP (interphalangeal), MCP (metacarpophalangeal), PIP (proximal interphalangeal), Flex (flexion), Abd (abduction).

Figure 5.4 (caption in previous page)

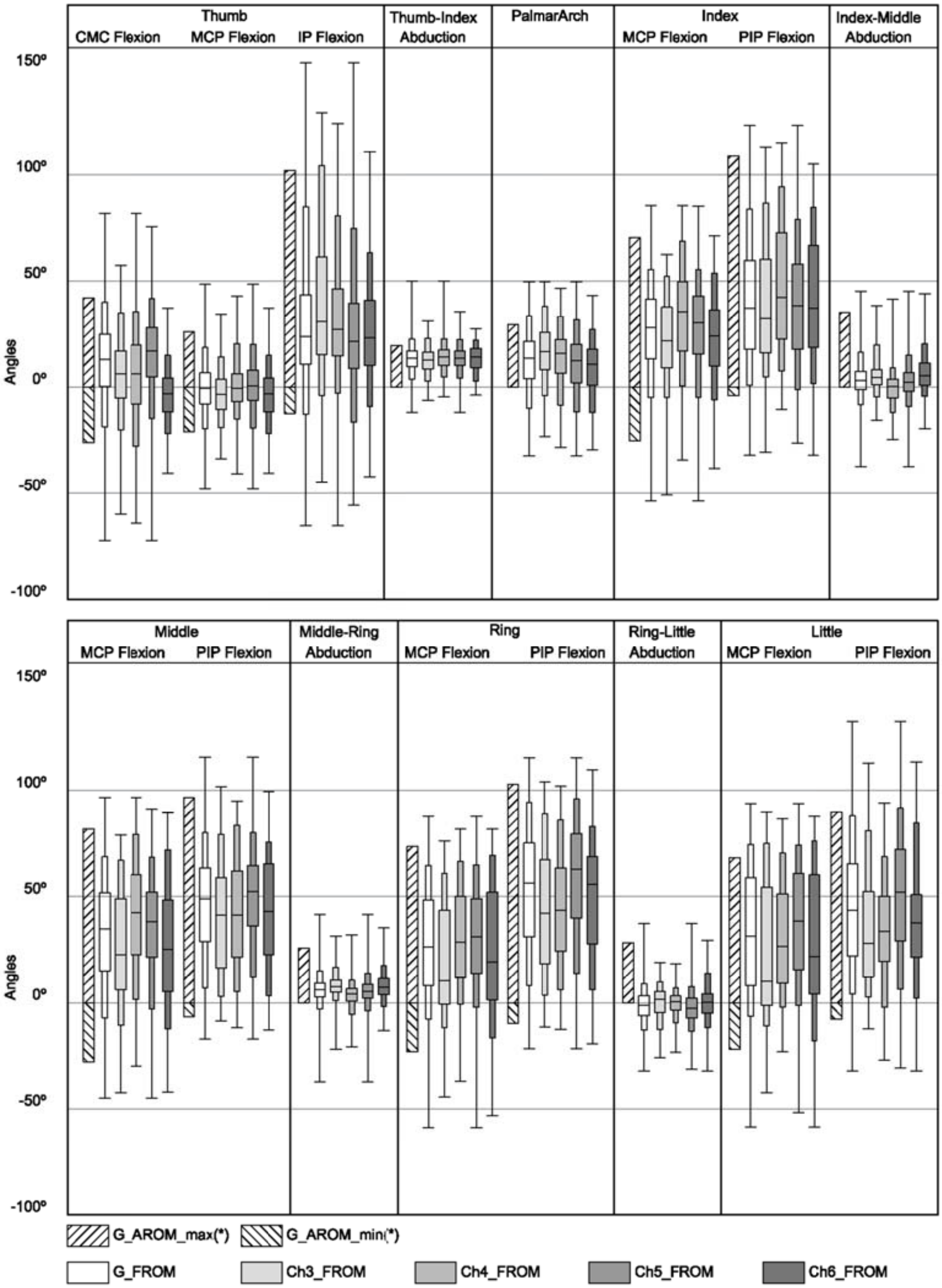

Figure 5.5 (caption in following page)

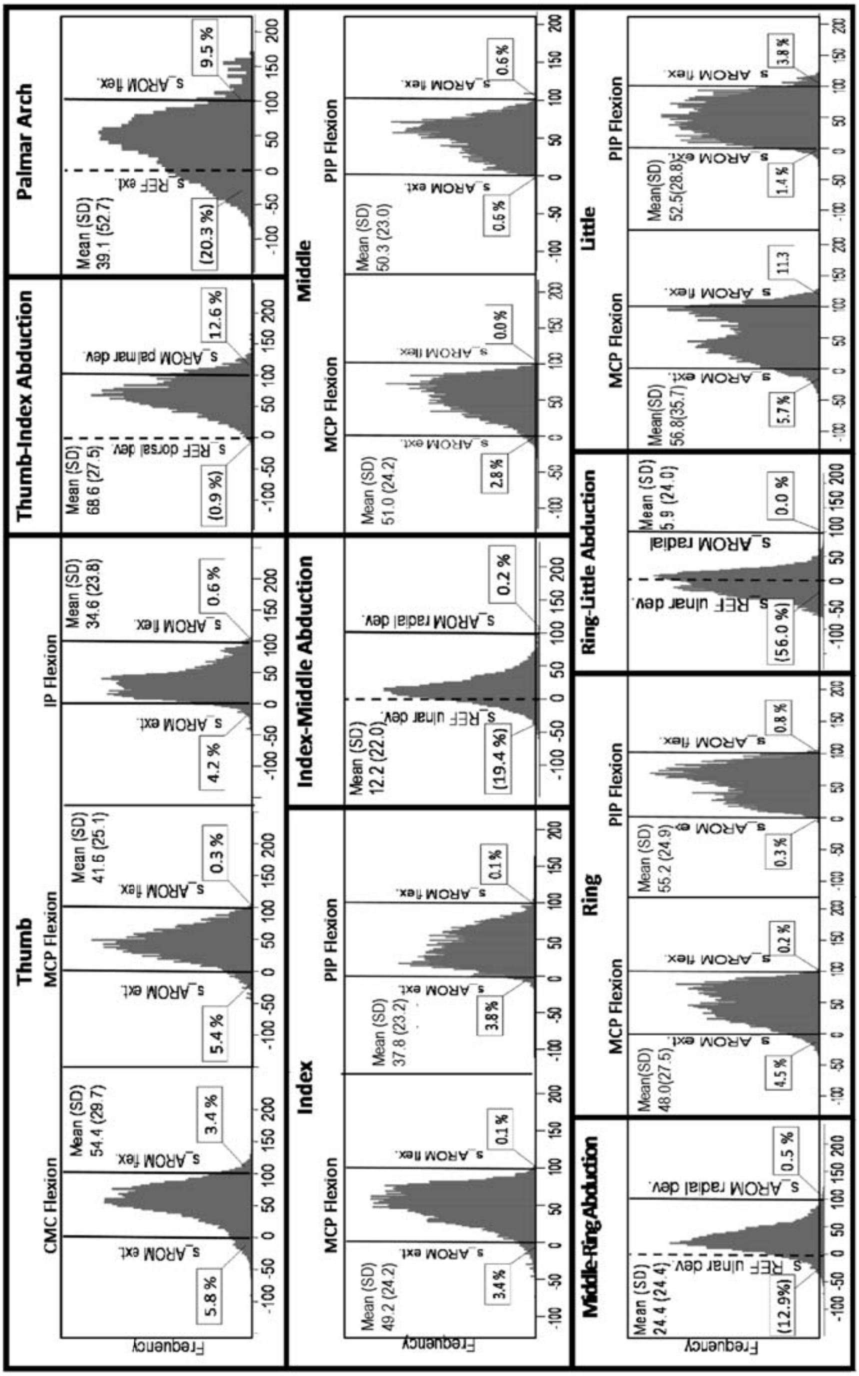

Figure 5.5. Comparison between subject-specific AROM (s_AROM) and percentage of time that each joint angle is used to perform the selected ADL: histograms represent the frequency of use of re-scaled angles from all the frames (time instants) for each the joint motion. Vertical lines have been drawn at 0 and 100, representing minimum and maximum s_AROM values. Dashed lines correspond to non-measured AROM values, so that a re-scaled angle of 0 corresponds to the angle obtained in the reference posture and not to the maximal achievable angle. The percentage of time beneath re-scaled angle 0 and over re-scaled angle 100 are also presented, while values between parentheses indicate that s_AROM was not measured and was substituted by the corresponding angle in the reference posture. Nomenclature: CMC (carpometacarpal), IP (interphalangeal), MCP (metacarpophalangeal), PIP (proximal interphalangeal), Flex (flexion), Abd (abduction).

5.4 Discussion

In this work, AROM values both globally and stratified by gender are provided for all hand joints of the right hand in right-handed subjects, except for DIP joints, although in some joints they are given only for the sense of flexion movement. AROM values of the palmar arching are a novelty. AROM values obtained for flexion of MCP and PIP joints and abduction of MCP joints of the fingers are in agreement with those reported in previous works (Hume et al. 1990; Bain et al. 2014; Coupier et al. 2015). Flexion ranges for MCP joints are a little smaller than reported elsewhere, probably due to the stiffness provided by the instrumented glove used for conducting the experiments. However, these comparisons have to be taken with care, because the postures used to obtain the AROM values are not reported in many cases, and may differ from ours.

AROM values of flexion of CMC, MCP and IP joints and abduction of the CMC joint of the thumb are also consistent with those reported previously (Hume et al. 1990; Tubiana 1980; Cerveri et al. 2008; Coupier et al. 2015). Comparison of CMC abduction and flexion AROM values with those reported by other works is cumbersome, as they present a high degree of variability (Dumas et al. 2008; Coupier et al. 2015; Hoppenfeld & Hutton 1984), probably due to a lack of consensus on the definition of these movements. Also, the AROM values for flexion and extension of the thumb MCP joint have to be taken with care, as the thumb MCP joint is somewhat flexed in the reference posture considered, thus providing high extension and low flexion AROM values. The mean flexion AROM for palmar arching, not previously reported in the literature, is about 30º. This angle has been measured over the knuckles (Figure 5.1) with respect to the hand resting on a flat surface. These data are relevant. Most research is focused only on the flexion capabilities of the fingers and the thumb, as they define the gross motion of the hand. However, a reduction in the ability of flexing the palmar arch would require a higher flexion of ring and little finger MCP joints, thus affecting the opposition between the thumb and the fingers.

The values of FROM reported when performing a representative set of ADL according to the ICF of the WHO, both globally and per ADL (G_FROM and ADL_FROM), are another relevant contribution of this work. Values of global FROM are also provided stratified by gender. Additionally, extreme and percentile values of the hand postures used for developing these ADL are provided globally and per ICF chapter (G_Postures and Ch_Postures).

AROM is commonly used as a reference goal for assessing the level of recovery achieved for hand functionality by medical and therapist staff. The comparison of AROM and FROM values obtained in this work may help to clarify the role of the AROM in the assessment of functionality. To complete all the activities tested, participants required the FROM values (G_FROM) described in Table 5.4, which are smaller than the G_AROM values for most joints. However, when comparing the G_AROM values with all values of G_Postures registered (Figure 5.4), angles at all joints exceed G_AROM bounds at specific moments for some subjects while performing the selected set of ADL. But at least 90% (approximately) of them are contained within the limits of the G_AROM values measured, consistently with the results from the comparison between G_AROM and G_FROM values, as well as from the results of the paired t-test comparing the s_AROM and s_FROM values. It is not strange that joint angles exceed the AROM values at specific moments, as hand joints during ADL might be passively forced to reach these values. This fact reinforces the proposal of computing the FROM as the 5th and 95th percentiles of the hand joint angles used, instead of directly using the extreme values recorded. Additionally, these comparisons show that using AROM as an indicator of the joint angle limits for establishing hand function may be useful but excessive in some cases, because the G_FROM values required to perform ADL are, in general, much lower than the AROM values (e.g., flexion of the thumb IP joint and PIP joint of the index finger). For these situations, the data provided here might be considered. The exceptions to this rule occur for the flexion of the little MCP joint and the palmar arch, the extension of the thumb MCP and IP joints, and the abduction of the thumb CMC joint, where the differences between AROM and FROM values are not significant or are very small. All these results are provided with respect to the postures that we have used to measure the AROM data, which in some cases may not be providing the maximum joint angles achievable, probably because the extreme values occur when a combination of movements is performed (e.g., circumduction of the thumb), and efforts were made to ensure the postures used for the AROM computation (selected according to classical indications) included just one pure movement, as they are more reproducible. This is a drawback of using AROM for the hand functional assessment. In any case, the exceeding values are not so high.

The FROM is quite dependent on the ADL, with values depending on the grasp types used for developing the activity, and with range of variation related to the required dexterity. For example, the activity 16 (Putting on a shoe and tying the shoelaces) requires a more flexed median posture than activity 21 (Drinking water), and a much higher range of joint flexion angles. Different social environments may require different ADL to be performed, so that in order to assess hand function different sets of ADL should be considered to represent the FROM. As FROM is highly dependent on the ADL, some differences among chapters are also observed in the distributions of Ch_Postures. For example, the 95th percentiles for some joints are higher in different chapters: in chapter 3 (Communication), for the thumb IP flexion and palmar arching, which agrees with handling a pen for writing, and for abduction of all fingers, compatible with typing on a PC keyboard; in chapter 4 (Mobility), for the CMC extension of the thumb and for MCP and PIP flexion of the index and middle fingers, which is compatible with grasping a door handle to open it; in chapter 5 (Self-care), for thumb CMC flexion and ring and little PIP flexion, which agrees with the fine manipulation grasps required in many activities in this chapter; in chapter 6 (Domestic life), for abduction of all fingers and for MCP extension of the ring and little fingers, which matches using a cloth for cleaning. These results have to be taken with care, as they are obviously dependent on the selection of the activities considered in each chapter. It is worth mentioning that global values per chapter presented have been obtained from a reduced set of representative activities.

Extreme values of postures used (previous AROM and FROM values) are important data to assess functionality, but also median values of hand postures (G_Postures and Ch_Postures) are relevant information as they represent the central posture of the joints required for performing ADL. This central posture should be considered for decision-making in clinical intervention. The central posture observed for the tasks considered in this work corresponds to a slightly flexed posture with neutral abduction of the fingers and the thumb, and the palm slightly arched. PIP and IP joints are more flexed than MCP joints (see relative values in Figure 5.4).

Another way of comparing AROM and FROM arises from using direct subject-specific values of AROM. In this work, this has been performed by calculating each FROM as the percentage of the subject-specific AROM (called s_AROM). From the histograms in Figure 5.5 it can be observed that, in those cases where both s_AROM bounds were measured, the distributions of FROM (measured as a percentage) present a bell-shaped profile, more or less centered within the s_AROM values, which means that the postures needed to perform ADL are mainly the central posture of each subject AROM. However, some exceptions also occur here. First, for the IP joint of the thumb, which is used mainly extended and flexed to a very small extent. This can be clinically relevant when a decision regarding an arthrodesis has to be made. Second, some joints present a bimodal or quasi bimodal distribution of FROM. This is the case of MCP and PIP flexion of the ring and little fingers. In these cases the central posture is not so relevant, but a wider range of postures should be considered for clinical purposes. Some distributions of FROM have longer tails than others and require a higher percentage of time beyond the measured AROM values. This is the case for extension and palmar deviation of the thumb CMC joint, extension of the thumb MCP joint, palmar arching, and flexion and extension of the little MCP joint. This means that this way of measuring the AROM for these particular movements and joints is not the best indicator of hand function.

The data presented in the tables of the appendix will allow clinicians to assess functionality. The loss of functionality for performing ADL of a person who has experienced a reduction of his/her AROM because of a lesion or pathology may be estimated from the values of these tables. As an example, consider the case of a worker with the middle PIP joint affected because of an accident so that his/her AROM is reduced to 20º/80º. If his/her normal values of flexion before the accident were 0º/100º (these values could be obtained from the non-affected hand), then his/her loss in AROM would be about 40% (20% in flexion, 20% in extension). From Table 5.8, one can infer that not being able to flex the middle PIP joint more than 80º means that the worker cannot adopt only 1% of the postures needed for handling a book and 2% of the postures required to open a door using a handle, but 40% of the postures needed for using a key to open a door. Conversely, being unable to adopt joint angles lower than 20º prevents the worker from achieving 48% of the postures needed for handling a book, but only 11% of the postures for opening a door and 6% of the postures for using a key to open a door. The use of these data to assess functionality is a novelty, but has to be used with caution. The complexity of the hand kinematics allows humans to substitute one grasp by another to perform ADL when impaired (Hume et al. 1990). Thus, in the case of a reduction of mobility of a specific joint, functionality to perform a specific activity might not be affected if the rest of the hand manages to overcome the limitations of that specific joint to perform this activity. Some works have tried to evaluate this compensatory mechanism by using different metrics such as the functional arc (Hume et al. 1990) or the reachable space (Kurillo et al. 2013; Pham et al. 2014) when grasping. In addition, other works have attempted to evaluate the FROM resulting from a reduction of the ROM of a specific joint achieved by constraining the joint with an orthosis. This is the case of Hayashi et al. (Hayashi et al. 2014), who established, by means of an orthosis limiting the flexion of the MCP joints of all fingers, that a flexion of 70º and an extension lag of 20º was enough for normal functionality, assessed through Jebsen and O'Connor tests (Program 2006). These findings can be compared with the estimations that may be performed using the data provided in the Appendix A. As an example, considering the G_AROM values reported in Table 5.4 (-25.3º/70.6º) for the MCP joint of the index finger, the constraints on the AROM considered in Hayashi et al. (Hayashi et al. 2014) correspond to re-scaled angles 21 and 99. From Table 5.9, we can observe that this constraint in the flexion of the MCP joint of the index finger would introduce a limitation of 0% in all the activities of self-care, thus in agreement with Hayashi's observation. According to Table 5.3, the reduction of extension would provide a higher limitation, ranging from 1% in eating with a fork or cutting with a knife, 5% in eating soup, 7% in brushing teeth or putting on pants, up to 33% or 37% in pouring or drinking water, respectively. These limitations from AROM reduction may be overcome by modifying the global hand posture, probably by demanding a greater extension of the thumb to reach the objects. In this case, these new angles required at the thumb joints may allow the action to be performed, but probably providing a less stable grasp and with more extreme angles at the thumb joints.

Finally, one limitation of these results is that the angles reported here include all the hand joints, even those corresponding to fingers that may not be participating in grasping the product, as well as reaching it; however, they are not expected to be very extreme angles. Another limitation of the work is that the number of activities selected as representatives of each chapter is limited, and a higher number of activities could be more enriching. Also worth noting as a limitation is the effect that the glove can have on the postures during the performance of the ADL. However, this is a minor disadvantage in comparison with the advantages of using an instrumented glove over the use of other less invasive systems with less precision, as visual recognition of postures, or other more accurate systems as motion capture systems with markers, where the problems of hiding do not allow measuring the hand motion during ADL. Despite these limitations, the data presented in this work could be used by clinicians to improve the current functional assessment performed, by checking the AROM of the hand joints of their patients.

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5.7 Appendix A

Detailed data of the ADL of each ICF chapter are presented in Tables 5.7 to 5.10, describing the percentages of time beneath re-scaled angles 0, 10, 20 and 30, and over 70, 80, 90 and 100. Values between parentheses indicate that the s_AROM was measured in only one of the motion senses, so that a re-scaled angle 0 corresponds to the angle in the reference posture and not to the maximal achievable angle. Nomenclature: CMC (carpometacarpal), IP (interphalangeal), MCP (metacarpophalangeal), PIP (proximal interphalangeal), Flex (flexion), Abd (abduction).

Table 5.7. Percentages of time requiring non achievable postures of ADL from chapter 3 Communication, for different reductions of subject-specific AROM (s_AROM): percentages of time beneath re-scaled angles of 0, 10, 20 and 30, and over 70, 80, 90 and 100, for chapter 3, classified per activity.

			1. Reading								**2.Writing**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	3	5	10	17	13	8	4	1	5	7	8	10	31	16	6	1
	MCP	Flex	5	15	30	50	2	0	0	0	8	15	26	35	9	3	0	0
	IP	Flex	2	16	41	66	0	0	0	0	0	2	7	15	58	44	20	6
Thumb-Index		Abd	(3)	(4)	(7)	(13)	(35)	(20)	(10)	5	(0)	(0)	(1)	(2)	(84)	(75)	(68)	36
Index	MCP	Flex	2	9	19	33	4	0	0	0	0	1	2	10	41	10	0	0
	PIP	Flex	1	15	57	82	1	0	0	0	0	2	5	7	33	14	6	0
Index-Middle		Abd	(15)	(47)	(78)	(92)	(0)	(0)	(0)	0	(25)	(41)	(73)	(86)	(1)	(0)	(0)	0
Middle	MCP	Flex	5	10	19	32	4	1	0	0	0	1	5	7	57	29	0	0
	PIP	Flex	3	29	55	78	1	1	0	0	0	5	7	8	18	6	4	3
Middle-Ring		Abd	(4)	(14)	(39)	(68)	(0)	(0)	(0)	0	(3)	(13)	(32)	(51)	(12)	(6)	(4)	3
Ring	MCP	Flex	9	19	35	59	3	1	0	0	0	2	5	12	57	27	1	0
	PIP	Flex	1	15	47	75	2	0	0	0	0	1	2	3	35	18	5	1
Ring-Little		Abd	(6)	(13)	(31)	(56)	(1)	(0)	(0)	0	(41)	(52)	(73)	(89)	(0)	(0)	(0)	0
Little	MCP	Flex	13	24	43	62	4	2	1	0	1	2	3	5	79	67	58	34
	PIP	Flex	2	24	50	71	2	1	0	0	0	1	3	5	33	16	6	2
Palmar Arch		Flex	(9)	(13)	(19)	(26)	(25)	(15)	(9)	6	(4)	(5)	(7)	(8)	(74)	(60)	(46)	43

			3.Talking by phone								**4. Typing numbers on the phone**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	12	15	20	32	6	1	1	0	12	16	22	35	7	1	0	0
	MCP	Flex	13	16	27	40	3	2	0	0	6	14	20	34	14	8	3	0
	IP	Flex	1	7	19	32	6	3	2	0	0	3	16	32	4	1	0	0
Thumb-Index		Abd	(1)	(4)	(12)	(19)	(10)	(5)	(3)	3	(3)	(7)	(14)	(22)	(6)	(3)	(3)	3
Index	MCP	Flex	20	27	35	51	0	0	0	0	2	9	17	31	8	3	1	0
	PIP	Flex	5	18	49	63	14	2	0	0	4	20	61	84	3	2	1	0
Index-Middle		Abd	(6)	(18)	(30)	(44)	(30)	(25)	(16)	4	(11)	(31)	(57)	(77)	(0)	(0)	(0)	0
Middle	MCP	Flex	12	17	26	41	9	2	0	0	8	15	26	42	14	8	0	0
	PIP	Flex	0	4	9	15	61	34	5	0	0	14	33	64	13	7	3	0
Middle-Ring		Abd	(11)	(16)	(27)	(49)	(12)	(8)	(4)	2	(4)	(8)	(19)	(47)	(3)	(1)	(1)	0
Ring	MCP	Flex	8	15	24	31	16	5	2	0	13	26	43	64	1	0	0	0
	PIP	Flex	0	3	9	13	68	44	9	0	0	12	30	61	19	12	4	0
Ring-Little		Abd	(36)	(49)	(66)	(81)	(0)	(0)	(0)	0	(6)	(10)	(23)	(34)	(5)	(2)	(1)	1
Little	MCP	Flex	5	8	13	19	47	41	29	9	14	28	43	62	9	2	1	0
	PIP	Flex	0	5	10	13	36	25	16	4	1	16	44	59	15	5	3	3
Palmar Arch		Flex	(23)	(28)	(38)	(50)	(14)	(9)	(3)	1	(26)	(31)	(36)	(44)	(22)	(10)	(5)	2

			5. Typing on PC							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	6	9	14	26	5	3	1	0
	MCP	Flex	3	5	13	32	4	1	0	0
	IP	Flex	0	5	23	40	0	0	0	0
Thumb-Index		Abd	(1)	(3)	(6)	(11)	(18)	(5)	(3)	1
Index	MCP	Flex	4	9	17	32	2	0	0	0
	PIP	Flex	0	2	11	37	0	0	0	0
Index-Middle		Abd	(8)	(36)	(67)	(85)	(0)	(0)	(0)	0
Middle	MCP	Flex	11	19	33	54	1	0	0	0
	PIP	Flex	0	3	13	23	4	1	0	0
Middle-Ring		Abd	(2)	(6)	(20)	(50)	(3)	(1)	(0)	0
Ring	MCP	Flex	22	39	58	74	0	0	0	0
	PIP	Flex	0	2	9	35	3	0	0	0
Ring-Little		Abd	(2)	(7)	(11)	(31)	(9)	(4)	(2)	1
Little	MCP	Flex	27	44	62	81	0	0	0	0
	PIP	Flex	0	11	41	65	0	0	0	0
Palmar Arch		Flex	(11)	(16)	(20)	(25)	(33)	(22)	(14)	9

Table 5.8. Percentages of time requiring non achievable postures of ADL from chapter 4 Mobility, for different reductions of subject-specific AROM (s_AROM): percentages of time beneath re-scaled angles of 0, 10, 20 and 30, and over 70, 80, 90 and 100, for chapter 4, classified per activity.

			6. Handling a book								**7. Using a key to open a door**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	9	12	16	23	21	11	4	2	23	31	43	57	6	3	2	1
	MCP	Flex	2	6	12	28	10	4	2	0	2	5	13	26	24	14	10	4
	IP	Flex	2	9	19	40	1	0	0	0	1	3	12	21	19	12	3	1
Thumb-Index		Abd	(0)	(0)	(1)	(2)	(62)	(44)	(27)	13	(1)	(2)	(3)	(5)	(58)	(44)	(27)	15
Index	MCP	Flex	7	11	19	32	11	4	0	0	1	2	6	14	52	38	23	5
	PIP	Flex	1	10	35	71	1	0	0	0	0	2	6	13	54	32	10	4
Index-Middle		Abd	(23)	(55)	(83)	(93)	(1)	(1)	(1)	0	(46)	(70)	(89)	(94)	(1)	(1)	(0)	0
Middle	MCP	Flex	4	7	11	22	22	8	0	0	1	3	7	15	44	28	14	1
	PIP	Flex	4	21	48	65	3	1	0	0	0	1	6	15	52	40	8	0
Middle-Ring		Abd	(26)	(38)	(63)	(80)	(0)	(0)	(0)	0	(17)	(36)	(62)	(79)	(0)	(0)	(0)	0
Ring	MCP	Flex	3	8	14	28	25	16	7	0	3	7	15	28	25	15	5	0
	PIP	Flex	1	13	42	64	3	1	0	0	0	1	5	16	46	28	3	0
Ring-Little		Abd	(41)	(54)	(70)	(85)	(0)	(0)	(0)	0	(22)	(36)	(54)	(69)	(3)	(2)	(1)	1
Little	MCP	Flex	1	4	12	23	40	31	21	9	4	13	25	39	21	16	8	4
	PIP	Flex	18	34	48	66	1	1	0	0	1	4	12	25	23	12	3	1
Palmar Arch		Flex	(3)	(6)	(9)	(14)	(36)	(29)	(22)	15	(30)	(36)	(41)	(46)	(19)	(13)	(8)	6

			8. Opening a door							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	4	7	11	18	33	20	9	4
	MCP	Flex	3	6	12	25	6	3	0	0
	IP	Flex	4	14	31	49	3	1	0	0
Thumb-Index		Abd	(0)	(1)	(3)	(8)	(48)	(38)	(26)	14
Index	MCP	Flex	0	2	5	12	36	15	3	0
	PIP	Flex	1	6	20	36	14	2	0	0
Index-Middle		Abd	(47)	(72)	(93)	(98)	(0)	(0)	(0)	0
Middle	MCP	Flex	0	1	3	7	41	24	5	0
	PIP	Flex	0	2	11	25	9	2	0	0
Middle-Ring		Abd	(30)	(47)	(67)	(82)	(0)	(0)	(0)	0
Ring	MCP	Flex	1	3	9	17	33	17	2	0
	PIP	Flex	0	2	8	18	8	2	1	0
Ring-Little		Abd	(41)	(55)	(69)	(83)	(0)	(0)	(0)	0
Little	MCP	Flex	1	5	12	21	40	27	14	3
	PIP	Flex	0	2	8	19	7	1	0	0
Palmar Arch		Flex	(12)	(18)	(25)	(34)	(31)	(21)	(14)	10

Table 5.9. Percentages of time requiring non achievable postures of ADL from chapter 5 Self Care, for different reductions of subject-specific AROM (s_AROM): percentages of time beneath re-scaled angles of 0, 10, 20 and 30, and over 70, 80, 90 and 100, for chapter 5, classified per activity.

			9. Turning on and off the faucet								**10. Washing and drying hands**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	10	19	25	33	6	3	1	0	13	16	22	29	14	8	5	3
	MCP	Flex	14	23	41	62	4	2	1	0	3	7	15	34	4	1	0	0
	IP	Flex	0	1	7	18	18	10	1	0	1	5	19	40	1	0	0	0
Thumb-Index		Abd	(0)	(1)	(2)	(5)	(55)	(46)	(27)	18	(5)	(9)	(14)	(22)	(24)	(13)	(7)	3
Index	MCP	Flex	6	8	14	21	14	2	0	0	7	12	20	34	11	4	1	0
	PIP	Flex	0	5	9	17	21	3	0	0	2	11	28	53	4	1	0	0
Index-Middle		Abd	(38)	(54)	(73)	(81)	(6)	(6)	(4)	3	(31)	(59)	(81)	(92)	(1)	(1)	(0)	0
Middle	MCP	Flex	0	1	2	10	46	28	8	0	5	10	19	33	11	3	0	0
	PIP	Flex	0	2	5	11	12	4	3	0	1	12	28	49	8	3	0	0
Middle-Ring		Abd	(47)	(67)	(81)	(90)	(0)	(0)	(0)	0	(15)	(32)	(57)	(74)	(2)	(1)	(0)	0
Ring	MCP	Flex	0	1	3	10	57	46	23	3	6	12	26	40	9	3	1	0
	PIP	Flex	0	1	3	8	38	21	5	0	1	6	23	43	9	3	1	0
Ring-Little		Abd	(69)	(81)	(88)	(94)	(0)	(0)	(0)	0	(25)	(42)	(62)	(77)	(1)	(1)	(1)	0
Little	MCP	Flex	0	1	6	9	67	61	54	33	6	12	23	35	15	10	6	3
	PIP	Flex	0	2	5	13	40	26	15	6	4	14	31	49	7	3	2	1
Palmar Arch		Flex	(14)	(21)	(30)	(37)	(25)	(17)	(13)	9	(12)	(18)	(25)	(35)	(20)	(14)	(10)	7

			11. Brushing teeth								**12. Putting toothpaste onto a toothbrush**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	5	7	10	14	39	21	10	5	3	7	10	14	47	27	13	6
	MCP	Flex	0	2	7	19	16	6	2	0	2	8	19	34	7	2	0	0
	IP	Flex	11	28	47	65	0	0	0	0	6	24	50	66	1	1	0	0
Thumb-Index		Abd	(1)	(2)	(4)	(7)	(47)	(28)	(14)	5	(0)	(1)	(2)	(7)	(50)	(32)	(16)	6
Index	MCP	Flex	2	4	7	11	29	7	1	0	1	3	6	13	18	4	1	0
	PIP	Flex	0	7	20	41	3	0	0	0	0	5	18	39	8	3	1	0
Index-Middle		Abd	(44)	(64)	(80)	(88)	(0)	(0)	(0)	0	(37)	(60)	(80)	(90)	(0)	(0)	(0)	0
Middle	MCP	Flex	1	2	5	15	21	6	1	0	1	2	7	16	14	2	0	0
	PIP	Flex	0	1	5	9	42	23	8	2	0	2	6	10	23	8	2	1
Middle-Ring		Abd	(11)	(29)	(46)	(63)	(2)	(0)	(0)	0	(12)	(27)	(48)	(66)	(1)	(1)	(0)	0
Ring	MCP	Flex	2	4	11	25	26	8	2	0	3	6	12	24	17	6	1	0
	PIP	Flex	0	0	3	7	63	46	20	5	0	0	4	6	38	15	3	0
Ring-Little		Abd	(42)	(53)	(66)	(77)	(2)	(2)	(1)	1	(34)	(45)	(62)	(75)	(2)	(0)	(0)	0
Little	MCP	Flex	6	9	14	21	48	40	29	17	3	6	13	20	36	28	18	5
	PIP	Flex	0	1	4	8	65	50	33	12	0	1	5	9	40	23	9	4
Palmar Arch		Flex	(36)	(42)	(50)	(58)	(11)	(8)	(5)	3	(19)	(23)	(27)	(33)	(24)	(14)	(9)	6

			13. Combing hair								**14. Putting on a shirt & fastening 2 buttons**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	5	7	11	16	44	28	16	8	2	3	5	8	55	34	19	10
	MCP	Flex	2	5	11	23	19	6	1	0	1	4	10	22	10	2	0	0
	IP	Flex	8	25	46	62	1	0	0	0	9	22	39	59	3	2	1	0
Thumb-Index		Abd	(2)	(3)	(6)	(11)	(44)	(25)	(9)	3	(1)	(1)	(2)	(5)	(67)	(49)	(28)	11
Index	MCP	Flex	7	11	19	30	10	3	0	0	2	5	9	16	21	5	0	0
	PIP	Flex	2	11	19	29	10	2	0	0	0	3	13	31	3	0	0	0
Index-Middle		Abd	(14)	(34)	(55)	(71)	(2)	(1)	(1)	1	(29)	(54)	(76)	(90)	(0)	(0)	(0)	0
Middle	MCP	Flex	2	4	12	23	14	3	0	0	1	2	7	15	20	4	0	0
	PIP	Flex	0	2	4	11	30	15	6	1	1	3	7	19	14	4	1	0
Middle-Ring		Abd	(13)	(23)	(41)	(56)	(3)	(1)	(0)	0	(14)	(25)	(49)	(71)	(1)	(0)	(0)	0
Ring	MCP	Flex	3	6	11	20	22	8	1	0	2	5	12	23	14	5	1	0
	PIP	Flex	0	1	5	11	37	15	3	0	1	1	5	13	14	3	1	0
Ring-Little		Abd	(40)	(59)	(73)	(83)	(1)	(0)	(0)	0	(21)	(34)	(50)	(65)	(1)	(1)	(0)	0
Little	MCP	Flex	2	4	9	14	45	37	25	12	5	9	17	26	20	14	7	3
	PIP	Flex	1	4	9	19	26	13	2	0	1	4	11	22	12	6	2	1
Palmar Arch		Flex	(19)	(23)	(28)	(37)	(24)	(18)	(13)	9	(18)	(23)	(30)	(37)	(19)	(13)	(7)	5

Table 5.9 Cont. I: Chapter 5. Self-care

			15. Putting on pants, buttoning and zipping them up								**16. Putting on a shoe & tying the shoelaces**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	5	7	11	16	39	24	13	6	4	7	10	14	44	29	15	7
	MCP	Flex	3	7	15	29	16	8	3	1	3	6	13	23	16	8	3	0
	IP	Flex	15	31	47	60	7	3	2	1	11	27	43	62	3	2	0	0
Thumb-Index		Abd	(0)	(1)	(2)	(5)	(59)	(46)	(30)	15	(0)	(1)	(3)	(5)	(46)	(31)	(19)	10
Index	MCP	Flex	2	4	7	12	28	12	1	0	1	4	8	15	21	5	0	0
	PIP	Flex	0	3	12	26	13	5	2	0	2	7	18	37	7	2	1	0
Index-Middle		Abd	(36)	(54)	(71)	(83)	(1)	(0)	(0)	0	(45)	(66)	(82)	(91)	(0)	(0)	(0)	0
Middle	MCP	Flex	1	2	5	11	26	8	1	0	2	4	10	19	13	4	0	0
	PIP	Flex	0	1	6	12	32	16	6	1	1	5	11	20	24	12	3	1
Middle-Ring		Abd	(22)	(35)	(52)	(70)	(1)	(1)	(0)	0	(21)	(33)	(50)	(66)	(1)	(1)	(0)	0
Ring	MCP	Flex	1	3	8	16	23	10	2	0	2	6	13	27	11	4	1	0
	PIP	Flex	0	1	5	11	36	18	5	1	0	1	7	16	31	16	6	2
Ring-Little		Abd	(36)	(49)	(61)	(74)	(2)	(1)	(1)	1	(31)	(41)	(54)	(65)	(3)	(2)	(1)	1
Little	MCP	Flex	2	4	8	15	35	23	13	5	2	6	12	25	21	14	6	3
	PIP	Flex	1	4	10	20	28	15	6	2	1	4	11	21	27	16	8	3
Palmar Arch		Flex	(21)	(27)	(33)	(40)	(23)	(15)	(10)	6	(15)	(20)	(25)	(32)	(27)	(19)	(12)	9

			17. Eating soup								**18. Cutting with a knife**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	7	9	13	19	34	15	4	1	2	4	7	10	50	33	14	4
	MCP	Flex	1	4	9	18	17	7	0	0	1	2	3	7	32	17	5	0
	IP	Flex	0	4	14	31	8	4	1	0	3	9	27	40	2	2	1	1
Thumb-Index		Abd	(1)	(1)	(3)	(6)	(23)	(13)	(6)	3	(0)	(0)	(1)	(3)	(46)	(12)	(5)	2
Index	MCP	Flex	1	4	5	8	23	5	0	0	0	0	1	4	46	18	2	0
	PIP	Flex	0	1	7	13	9	0	0	0	21	51	77	85	1	0	0	0
Index-Middle		Abd	(39)	(63)	(80)	(89)	(0)	(0)	(0)	0	(19)	(43)	(67)	(81)	(0)	(0)	(0)	0
Middle	MCP	Flex	0	1	2	7	61	27	3	0	1	1	3	5	44	22	3	0
	PIP	Flex	0	2	4	9	17	1	0	0	0	1	2	3	41	10	0	0
Middle-Ring		Abd	(27)	(47)	(68)	(85)	(0)	(0)	(0)	0	(9)	(23)	(43)	(59)	(5)	(2)	(1)	0
Ring	MCP	Flex	1	2	3	6	52	20	4	0	1	2	3	6	67	45	17	0
	PIP	Flex	0	2	4	5	52	14	5	0	0	1	2	3	78	60	20	0
Ring-Little		Abd	(66)	(82)	(91)	(95)	(0)	(0)	(0)	0	(55)	(72)	(84)	(90)	(1)	(0)	(0)	0
Little	MCP	Flex	1	2	4	5	76	61	39	19	1	2	3	4	85	78	66	35
	PIP	Flex	0	2	4	5	58	32	10	2	0	1	3	4	82	61	36	13
Palmar Arch		Flex	(13)	(16)	(21)	(26)	(45)	(35)	(27)	22	(38)	(48)	(58)	(66)	(9)	(7)	(4)	3

			Table 5.9 Cont. II: Chapter 5. Self-care															
			19. Eating with a fork								**20. Pouring water**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	4	4	5	8	43	24	9	4	1	2	3	6	38	18	12	4
	MCP	Flex	0	1	3	7	34	23	12	1	27	39	60	80	0	0	0	0
	IP	Flex	3	12	39	64	2	0	0	0	0	3	8	15	12	4	0	0
Thumb-Index		Abd	(0)	(1)	(3)	(11)	(45)	(24)	(9)	2	(1)	(2)	(4)	(6)	(86)	(84)	(79)	67
Index	MCP	Flex	0	0	1	5	40	14	3	0	13	19	33	60	0	0	0	0
	PIP	Flex	8	28	50	60	7	5	0	0	0	3	11	29	0	0	0	0
Index-Middle		Abd	(39)	(68)	(82)	(91)	(0)	(0)	(0)	0	(0)	(6)	(32)	(49)	(6)	(2)	(0)	0
Middle	MCP	Flex	0	1	2	4	32	9	0	0	2	10	17	23	8	0	0	0
	PIP	Flex	0	1	3	5	28	11	2	0	0	4	15	23	0	0	0	0
Middle-Ring		Abd	(12)	(21)	(41)	(59)	(7)	(5)	(2)	0	(6)	(11)	(23)	(40)	(5)	(0)	(0)	0
Ring	MCP	Flex	0	1	3	6	30	8	3	1	4	10	21	35	8	0	0	0
	PIP	Flex	0	1	3	4	72	54	30	5	0	4	15	31	0	0	0	0
Ring-Little		Abd	(57)	(65)	(83)	(91)	(1)	(0)	(0)	0	(12)	(17)	(30)	(45)	(10)	(7)	(5)	4
Little	MCP	Flex	1	2	3	5	72	60	39	11	9	18	22	34	8	4	1	0
	PIP	Flex	0	1	3	4	75	68	51	19	6	18	32	60	0	0	0	0
Palmar Arch		Flex	(51)	(61)	(66)	(72)	(10)	(6)	(4)	2	(8)	(10)	(15)	(23)	(40)	(36)	(19)	13

			21. Drinking water							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	1	2	5	6	33	12	5	0
	MCP	Flex	29	42	58	78	1	0	0	0
	IP	Flex	0	3	9	17	28	8	2	0
Thumb-Index		Abd	(1)	(2)	(4)	(5)	(86)	(83)	(80)	66
Index	MCP	Flex	15	22	37	64	0	0	0	0
	PIP	Flex	0	2	9	20	0	0	0	0
Index-Middle		Abd	(3)	(15)	(36)	(57)	(0)	(0)	(0)	0
Middle	MCP	Flex	5	12	22	35	2	0	0	0
	PIP	Flex	0	3	12	25	0	0	0	0
Middle-Ring		Abd	(2)	(7)	(23)	(36)	(16)	(9)	(3)	0
Ring	MCP	Flex	11	20	28	40	0	0	0	0
	PIP	Flex	1	6	18	42	0	0	0	0
Ring-Little		Abd	(10)	(17)	(36)	(48)	(9)	(5)	(3)	2
Little	MCP	Flex	10	17	24	33	21	10	2	0
	PIP	Flex	4	18	46	67	3	0	0	0
Palmar Arch		Flex	(10)	(17)	(25)	(33)	(25)	(19)	(11)	7

Table 5.10. Percentages of time requiring non achievable postures of ADL from chapter 6 Domestic life, for different reductions of subject-specific AROM (s_AROM): percentages of time beneath re-scaled angles of 0, 10, 20 and 30, and over 70, 80, 90 and 100, for chapter 6, classified per activity.

			22. Using a spray								**23. Cleaning using a cloth**							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**	**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	8	11	15	21	26	13	7	4	4	7	10	15	29	18	9	4
	MCP	Flex	7	15	27	40	5	2	0	0	1	5	15	25	16	8	2	0
	IP	Flex	2	6	20	37	5	1	0	0	1	10	32	46	1	0	0	0
Thumb-Index		Abd	(0)	(1)	(1)	(3)	(67)	(47)	(31)	15	(2)	(8)	(13)	(25)	(13)	(6)	(2)	0
Index	MCP	Flex	4	8	15	26	5	1	0	0	6	12	17	31	3	0	0	0
	PIP	Flex	2	5	12	34	5	1	0	0	6	25	58	76	1	0	0	0
Index-Middle		Abd	(18)	(50)	(74)	(90)	(0)	(0)	(0)	0	(16)	(33)	(53)	(71)	(1)	(0)	(0)	0
Middle	MCP	Flex	3	7	13	25	9	1	0	0	12	22	40	59	1	0	0	0
	PIP	Flex	0	3	9	25	5	1	0	0	5	19	36	55	16	6	2	1
Middle-Ring		Abd	(14)	(22)	(47)	(71)	(1)	(0)	(0)	0	(2)	(8)	(21)	(35)	(17)	(11)	(7)	4
Ring	MCP	Flex	3	8	16	29	17	7	1	0	18	33	55	72	1	0	0	0
	PIP	Flex	0	0	6	21	14	3	0	0	2	15	31	42	31	19	7	2
Ring-Little		Abd	(26)	(38)	(56)	(73)	(0)	(0)	(0)	0	(2)	(7)	(19)	(35)	(27)	(19)	(12)	8
Little	MCP	Flex	4	9	16	27	32	23	13	4	20	34	49	60	4	1	0	0
	PIP	Flex	1	4	15	35	6	2	0	0	6	18	30	40	37	29	15	3
Palmar Arch		Flex	(16)	(21)	(27)	(35)	(19)	(12)	(8)	4	(23)	(29)	(34)	(42)	(12)	(7)	(4)	3

			24. Ironing							
% of AROM reduction			**0**	**10**	**20**	**30**	**70**	**80**	**90**	**100**
Thumb	CMC	Flex	12	17	21	25	18	8	2	1
	MCP	Flex	22	31	38	52	5	3	2	0
	IP	Flex	7	17	33	46	3	0	0	0
Thumb-Index		Abd	(0)	(1)	(1)	(2)	(75)	(57)	(43)	26
Index	MCP	Flex	1	2	7	13	23	8	2	0
	PIP	Flex	0	1	4	11	36	8	0	0
Index-Middle		Abd	(8)	(25)	(42)	(55)	(5)	(3)	(2)	1
Middle	MCP	Flex	1	2	4	8	54	32	6	0
	PIP	Flex	0	1	3	7	31	6	0	0
Middle-Ring		Abd	(15)	(28)	(42)	(55)	(3)	(0)	(2)	0
Ring	MCP	Flex	1	3	6	12	67	49	16	0
	PIP	Flex	0	0	2	7	13	0	3	0
Ring-Little		Abd	(37)	(52)	(72)	(88)	(1)	(1)	(1)	1
Little	MCP	Flex	1	3	7	11	74	72	58	33
	PIP	Flex	0	1	5	11	3	0	0	0
Palmar Arch		Flex	(38)	(46)	(56)	(66)	(5)	(2)	(0)	1

Chapter
06

FUNCTIONAL HAND ASSESSMENT BY DIMENSIONAL REDUCTION OF ITS KINEMATICS

English translation of the original Spanish version presented at the
XXI Spanish Congress of Mechanical Engineering

ABSTRACT, KEY TERMS & ABBREVIATIONS

Abstract

The large number of degrees of freedom of the human hand makes it difficult to study its kinematics. Several attempts have been made to reduce the dimensionality of the problem by identifying kinematic synergies through the application of principal component analysis (PCA). The aim of this work is to study the use of these synergies in the functional assessment of subjects with hand pathologies. To do so, an experiment was designed to be carried out on 24 healthy and two pathological subjects. First, all the subjects completed several strength (cylindrical and pinch grasps) and skill tests (Purdue and Box & Block test) that are commonly used in the clinical setting for the functional assessment of the hand. The posture of the hand was later recorded with an instrumented glove while the subjects performed 24 representative activities of daily living from the WHO's International Classification of Functioning, Disability and Health (ICF). The 16 angles recorded were filtered, and those corresponding to the healthy subjects were reduced by means of PCA to five factors explaining 73.7% of the variance. To assess the functionality of the hand in the pathological subjects, the values of the angles recorded for them were compared with the reference sample in two different ways: (1) by identifying what percentile of posture centrality and dispersion, and velocity values they would correspond to, and (2) by means of a hierarchical cluster analysis. Lastly, the synergies and the corresponding explained variance were compared in the pathological subjects with respect to the reference sample. From the analysis of the results it can be inferred that the use of dimensional reduction can be a valid objective tool for detecting alterations in functionality.

Key terms

Hand, functional assessment, principal component analysis, ICF.

Abbreviations:

ADL: activities of daily living
AROM: active range of motion
ICF: International Classification of Functioning, Disability and Health
PCA: Principal component analysis
WHO: World Health Organization

6.1 Introduction

The hand plays a fundamental role in performing activities of daily living (ADL). Human beings use their hands in five out of the eight daily hours, after having discounted the time devoted to work and sleeping (Vergara et al. 2014). Therefore, the individual's self-sufficiency largely depends on the capability of the hand to perform ADL.

The functional assessment of the pathological or injured hand is crucial in clinical decision-making, in establishing rehabilitation strategies and also in the evaluation of the level of disability. There are different approaches to the functional analysis of the hand (Lee & Jung 2015). The methods currently used are focused on three aspects: grip strength evaluation (basically cylindrical and pinch), maximum joint ranges of motion and either the application of tests that evaluate different aspects such as dexterity, eye-hand coordination or mobility, or subjective questionnaires about functionality. These tests are specific for each pathology and, as the questionnaires, are highly subjective (Metcalf et al. 2007; Lemmens et al. 2012). These methodologies make it possible to evaluate up to a certain extent the level of recovery of the hand, but do not directly analyse its functionality in the performance of ADL needed for personal autonomy, this being understood as the capacity to carry out those activities without the need of external help.

There is, therefore, an obvious need for global, objective methods of functional assessment (Metcalf et al. 2007; Lemmens et al. 2012) that take into account functionality in performing ADL. In fact, one study reveals that 97.5% of therapists consider essential the use of rehabilitation strategies based on the performance of ADL (Powell & von der Heyde 2014). To achieve this goal it is necessary to agree on what ADL should be considered in the assessment, and to advance in the quantification of the different aspects that describe performance of the ADL. With regard to what ADL should be taken into account, a good reference is the ICF (WHO 2001) published by the WHO, since it has been postulated as a valid reference for the assessment of aspects related with health (Lindner et al. 2010). As regards the quantitative assessment of the performance of ADL, kinematic analysis has been proved to yield good results in the evaluation of the functionality of the arm (van Dokkum et al. 2014), and thus several attempts have been made to analyse the kinematics of the hand in ADL (Hume et al. 1990; Hayashi & Shimizu 2013; Bain et al. 2014). Nevertheless, one of the main problems in its use lies in the kinematic complexity of the hand, with 25 degrees of freedom. The studies in the literature have therefore been limited to establishing functional ranges of motion.

Although the large number of degrees of freedom of the hand complicates its kinematic analysis, the movements of the hand joints are not independent due to both the mechanical couplings-because of the connections of tendons and the multi-digit insertions of extrinsic finger muscles- (el-Badawi et al. 1995), and the neuronal couplings -via the innervation of a single cortical motor neuron in several spinal motor neuron pools- (Santello et al. 2013). In fact, several studies have offered evidence of the existence of synergies by applying principal component analysis (PCA) to the human grasp (Santello et al. 2002; Santello et al. 1998; Braido & Zhang 2004; Thakur et al. 2008). This study proposes the use of the method of dimensional reduction by means of PCA as a way to carry out functional assessment of the hand while performing ADL, based on kinematic analysis.

6.2 Materials and method

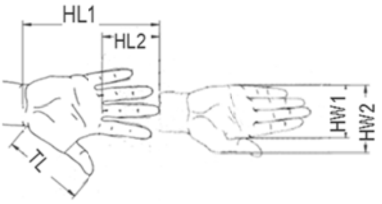
6.2.1 Description of the experiment

The experiment was designed in compliance with the Declaration of the World Medical Association and was approved by the University Ethics Committee. Twenty-four subjects (12 females and 12 males) participated, all of whom were right-handed, were free from hand pathologies or injuries and gave their informed consent. The ages of the subjects ranged intentionally between 18 and 50 years, in order to prevent kinematic alterations due to joint degeneration from ageing, and with a distribution of hand sizes that was representative of the population (see characteristics in Table 6.1). The same experiment was later applied to two other right-handed subjects, who had recently recovered from pathological events, both of whom were considered to have been fully recovered The first subject was a man who had a severe trauma in his right hand following an accident at work (injury by circular saw) twelve months before. His radial and ulnar arteries, median nerve, radial sensitive nerve and sensitive cuvital nerve, as well as multiple tendons were repaired in an emergency surgery. The second subject was a woman who had had a stroke that affected her right body thirteen months before.

The experiment consisted in two clearly differentiated parts. In the first part, anthropometric data (Table 6.1) and a series of measurements commonly used for assessment were collected: (i) measurement of strength in different grasps following the standards usually employed in assessment – cylindrical grip (Cyl), lateral pinch (Lat), 2-finger pinch (2P) and 3-finger pinch (3P); (ii) application of the two dexterity tests, 'Purdue Pegboard Test' and 'Box & Block Test'; (iii) and lastly measurement of the active ranges of motion (AROM), asking the subject to adopt a series of postures in accordance with Clarkson's indications (Clarkson 2012). For the strength measurements a Biometrics© dynamometer and pinchmeter was used. Three 6-second recordings in each hand were performed, alternating between hands and allowing one minute's rest between measurements, and average across the three trials was considered. The Purdue test determines whether fine handling skill and hand-eye coordination are compromised, and consists in the subject inserting as many pegs as possible in a series of holes on a board. The test consists of four parts: the first three allow the therapist to infer whether brain damage can be suspected (two of them evaluate dexterity in each hand in isolation, and the third does the same while they work simultaneously). The fourth is used to evaluate handling capacity oriented towards establishing the suitability for work for a specific workplace (it assesses non-simultaneous collaborative work while assemblies are being performed). The Box & Block test assesses unilateral gross dexterity, and is used in the diagnosis of multiple sclerosis, stroke or traumatic brain damage. It consists in moving as many blocks as possible, by picking them up one by one, from one compartment in a box to another within a specified time. The process is carried out first with the right hand and is then repeated with the left. A right-hand, 18-sensor instrumented glove (Cyberglove Systems LLC; San Jose, CA) was used to measure AROM. A previously validated calibration protocol (Gracia-Ibáñez et al. 2016a) was used to obtain the angles of 16 hand joints from the data recorded by the sensors.

Table 6.1. Characteristics of the study sample

	Age	HL1	HL2	HW1	HW2	TL
	Data of the study sample					
Minimum	20	158	93	72	82	96
Maximum	46	205	122	95	110	130
Mean	33.0	186.0	109.1	81.6	96.9	112.6
Std. dev.	8.8	11.3	7.4	6.5	8.3	8.3
S1 (injury)	47	194	119	112	95	114
S2 (stroke)	67	174	100	93	82	107



In the second part of the experiment, conducted in the laboratory and with the same precise instructions for everyone, the subjects performed 24 ADL from the WHO's ICF in which significant use of the right hand is required (Table 6.2). The kinematics of the hand were recorded (75 Hz) during the performance of these ADL with the glove and the 16 angles were obtained using the above-mentioned protocol. The initial and final instants in which the hand was at rest were cut off, and the recordings were later filtered (2nd-order low-pass Butterworth filter, applied in both backward and forward directions, normalised cut-off frequency = 0.1).

6.2.2 Data analysis

First of all, the strength, AROM and dexterity values of the reference sample were compared with those from the literature to check their normality. Then dimensional reduction was applied to the (filtered) joint angles that were recorded during the performance of the 24 ADL by the 24 subjects in the reference sample. To do so a PCA (eigenvalue>1, Varimax rotation, calculation of normalised factors) was performed on the 16 joint angles that were recorded. As recorded time was different between ADL, in this calculation data were weighted so that all ADL had the same weight regarding time. The scores of these factors were calculated during each of the 24 ADL for each subject (healthy and pathological), together with their time derivatives (velocities). Finally, 8 statistics (mean, standard deviation, minimum and maximum, 25th, 50th, 75th percentiles and interquartile range) of the scores and velocities were calculated for each subject in the reference sample. In all, the 24 recordings from all the ADL for each subject, properly weighted, were represented globally by means of 8 posture and 8 velocity parameters for each of the factors obtained in the PCA. The same 8 parameters were obtained for each subject and each ADL, individually.

With the aim of evaluating the functionality of the hand of the pathological subjects different analyses were performed to compare them with those of the sample of healthy subjects (reference sample). First, the strength, AROM and dexterity data were compared to determine the percentile in which each pathological subject was situated. Second, the overall performance of the ADL was compared, based on the percentile occupied by each pathological subject in the 16 statistics calculated globally (also weighted). A third comparison was performed by means of 24 hierarchical cluster analyses (grouping method: square of the euclidean distance to the centroid), one for each ADL, with the 8 statistics per ADL of all the subjects (healthy and pathological) and observing the grouping of the subjects. Lastly, a PCA was performed for each subject (healthy and pathological), with the same parameters as previous PCA but individually for each subject, and the principal components were obtained. Both the explained variance of these new components and their similarity with those obtained globally for the reference sample were compared. Similarity between components was assessed through the angle of deviation among the direction vectors of the principal components.

Table 6.2. ADL selected and recorded.

ICF chapter	ICF area	ADL selected	Body posture
3. Communication	d325. Communicating with - receiving - written messages	1. Reading	Seated
	d345. Writing messages	2. Writing	Seated
	d360. Using communication devices and techniques	3. Speaking by phone	Seated
		4. Dialling numbers on the phone	Seated
		5. Writing using the keypad	Seated
4. Mobility	d430. Lifting and carrying objects	6. Handling a book	Standing
	d440. Fine hand use	7. Unlocking a door with a key	Standing
	d445. Hand and arm use	8. Opening a door	Standing
5. Self-care	d520. Caring for body parts	9. Turning a tap on and off	Standing
		10. Washing and drying hands	Standing
		11. Cleaning teeth	Standing
		12. Putting toothpaste on a toothbrush	Standing
		13. Combing hair	Standing
	d540. Getting dressed	14. Putting a shirt on and doing buttons up	Standing
		15. Putting on trousers, doing up button and zip	Standing
		16. Putting shoes on and tying laces	Seated
	d550. Eating	17. Eating soup	Seated
		18. Cutting with a knife	Seated
		19. Eating with a fork	Seated
	d560. Drinking	20. Pouring water	Seated
		21. Drinking water	Seated
6. Domestic life	d640. Doing housework	22. Using a spray	Standing
		23. Cleaning with a cloth	Standing
		24. Ironing	Standing

6.3 Results

The strength values that were recorded (Table 6.3) are within the normal range for the subjects in the reference sample (Lorenzo-Agudo et al. 2007; Fain & Weatherford 2016; Mathiowetz et al. 1985; Nilsen et al. 2012), although they are slightly lower than the mean values in the literature. This is probably because the sample consists of persons who carry out work that does not require manual strength (academic setting or similar). In the case of the pathological subject S1, a clear very considerable decrease in strength can be observed in the right hand, while this is not the case of S2, whose values are within the normal range.

Table 6.3. Strength values recorded (kg)

	Right hand				Left hand			
	Cil	Lat	2P	3P	Cil	Lat	2P	3P
	Reference samples Males / Females							
Minimum	27.3 / 15.8	6.4 / 4.2	3.6 / 2.3	4.3 / 3.7	23.7 / 16.8	5.8 / 3.7	3.2 / 2.0	4.1 / 3.5
Maximum	48.3 / 28.9	24.1 / 7.0	6.6 / 5.0	10.8 / 6.3	45.2 / 23.5	21.9 / 6.0	6.6 / 4.4	9.7 / 5.7
Mean	36.8 / 22.2	9.6 / 5.6	5.0 / 3.6	7.4 / 5.1	34.2 / 19.8	8.9 / 5.0	4.6 / 3.1	6.9 / 4.3
Std. dev.	6.7 / 3.4	4.7 / 0.8	1.0 / 0.8	1.8 / 0.7	6.8 / 2.3	4.2 / 0.7	1.0 / 0.7	1.8 / 0.7
Pathological subjects (in brackets, the percentile with respect to the reference sample)								
S1- Male	23.6 (< 0)	5.7 (< 0)	4.0 (17)	4.0 (< 0)	42.6 (89)	7.0 (24)	5.1 (76)	6.9 (56)
S2 - Female	27.7 (97)	5.6 (42)	3.5 (42)	4.6 (18)	22.9 (90)	4.7 (36)	2.4 (8)	3.9 (33)

The AROM values recorded for the subjects in the reference sample (Table 6.4) are also within the normal range (Gracia-Ibáñez et al 2016b). The pathological subjects present some AROM outside the reference sample range (dark grey), and with values in extreme percentiles (in light grey below the 10th percentile). It can be seen how AROM is much more affected for subject S1 than for subject S2: S2 only presents values outside the range in the thumb, and values below the 10th percentile in flexion of the metacarpophalangeal joints of the index and ring fingers, and in the proximal interphalangeal joint of the index finger. Conversely, S1 presents values outside the reference sample range for both the thumb and the proximal interphalangeal joints of the fingers, in addition to values below the 10 th percentile in the flexions of several metacarpophalangeal joints.

Table 6.5 shows the data collected in the Purdue dexterity test. As expected, according to these values the subjects in the reference sample are not suspected of having any brain damage, in compliance with the instructions for using the test. In view of the results obtained with the right hand and on simultaneous work, this would, however, be suspected in both the pathological subjects. Again, the values of the reference sample are slightly lower than the normal mean values provided by the manufacturer (manufacturer's reference sample: male and female factory workers between 16 and 52 years of age). An important alteration was observed in both pathological subjects in terms of the number of pegs for the right hand, as well as in simultaneous work, which highlights the existence of a problem in fine handling.

Table 6.6 shows the data obtained in the Box & Block dexterity test, together with the normal values (age range 20-49 for the reference sample, specific age for each pathological subject). Again, the values for the subjects in the reference sample are within the normal range, while a deficit can be seen in the right hand of subject S1, and in both hands in subject S2.

Table 6.4. AROM (°) of the right hand

			Reference Sample	Pathological Subjects	
Finger	Joint (*)	Movement	Mean (Std. dev.)	S1 (The percentile with respect to the reference sample given in brackets)	S2
Thumb	CMC	Flexion /	42.9 (9.7) 25.6	35.8 (14) / -6.9 (< 0)	36.0 (15) / -5.7 (< 0)
		Abducción	19,8 (3,7)	12.4 (< 0)	16.4 (23)
	MCP	Flexion / Extension	26.5 (9.2) 20.1	28.7 (68) /12.1 (23)	28.2 (67) / 19.0 (43)
	IP	Flexion / Extension	101.1 11.7	24.1 (< 0) / -3.2 (< 0)	28.5 (< 0) / 15.8 (76)
Palmar arch		Flexion	29,0 (8,4)	17,0 (34)	15.0 (33)
Index	MCP	Flexion / Extension	70.3 (9.1) 24.5	70.3 (43) / 15.6 (52)	57.0 (9) / 15.6 (52)
		Abduction	34,6 (5,9)	35.9 (76)	36.2 (76)
	PIP	Flexion / Extension	108.9 3.8 (4.2)	50.0 (< 0) / -6.8 (< 0)	94.9 (11) / 0.0 (0)
Middle	MCP	Flexion / Extension	81.9 81.9	60.1 (3) / 15.8 (39)	59.3 (3) / 21.4 (61)
	PIP	Flexion / Extension	96.6 (9.7) 6.3 (4.7)	46.5 (< 0) / 0.0 (0)	95.6 (43) / 6.9 (57)
Ring	MCP	Flexion / Extension	73.6 (8.9) 23.0	59.4 (7) / 2.8 (27)	62.2 (8) / 18.0 (58)
		Abduction	25,5 (5,7)	24.2 (65)	29.2 (86)
	PIP	Flexion / Extension	102.9 9.4 (6.4)	53.6 (< 0) / 0.0 (0)	99.5 (26) / 4.4 (53)
Little	MCP	Flexion / Extension	68.6 (6.9) 21.7	78.8 (93) / 5.1 (33)	60.9 (17) / 23.7 (75)
		Abduction	34,7 (5,7)	34.2 (63)	26.6 (33)
	PIP	Flexion / Extension	90.0 7.9 (8.3)	33.7 (< 0) / -7.3 (< 0)	105.2 (97) / 8.6 (77)

(*) CMC: Carpometacarpal; MCP: Metacarpophalangeal; IP: Interphalangeal, PIP: Proximal interphalangeal.

Table 6.5. Values obtained in the Purdue Pegboard test

	Right	Left	Simultaneous	Sum	Assembly
	Reference sample				
Mean (Std. dev.)	16.5 (1.5)	14.9 (2.0)	15.6 (5.4)	44.4 (4.4)	41.6 (5.7)
	Pathological Subjects				
S1	6	16	3	25	12
S2	7	10	5	22	14

Table 6.6. Values obtained BOX & BLOCK

	Reference Sample		**Normal values** (Mathiowetz et al. 1985)	
	Male	Female	Male	Female
Hand	Mean (Std. dev.)	Mean (Std. dev.)	Mean (Std. dev.)	Mean (Std. dev.)
Right	79.0 (6.8)	82.4 (6.9)	82.8 (3.8)	84.5 (2.5)
Left	77.1 (6.0)	77.3 (5.3)	81.2 (3.7)	81.0 (2.1)
	Pathological Subjects		**Normal values** (Mathiowetz et al. 1985)	
	S1	S2	Hombre	Mujer
Right	52.0	48.0	76.9 (9.2)	72.0 (6.2)
Left	78.0	54.0	75.8 (7.8)	71.3 (7.7)

Figure 6.1 shows the 5 principal components (factors) that were obtained on applying the PCA to the reference sample, which explained 73.7% of the variance. *PC_1* represents the flexion of the interphalangeal joints, that is, *arching of fingers (FArc)*; *PC_2* is a combination of abduction of the fingers, except for the thumb, with flexion of the metacarpophalangeal joints, that is, *closure (Clos)*; *PC_3* represents *palmar arching (PArc)*; *PC_4* represents the *lateral opposition of the thumb to the index*, as required for the lateral pinch (*LatP)*; and finally, *PC_5* represents the *pad-to-pad opposition* of the thumb to the little finger *(Opps)*.

Table 6.7 shows the comparison of the statistics representing posture and velocity.

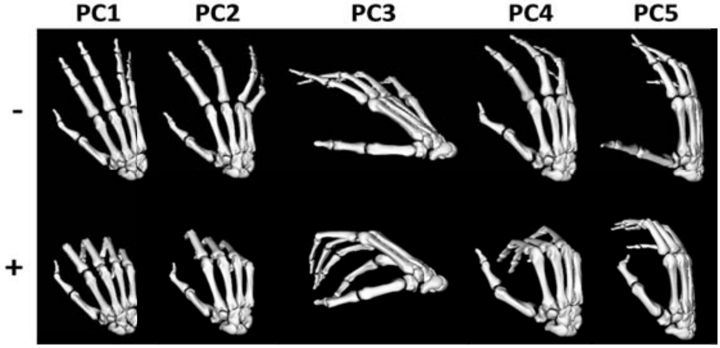


Figure 6.1. Principal components obtained from the reference sample while performing the ADL.

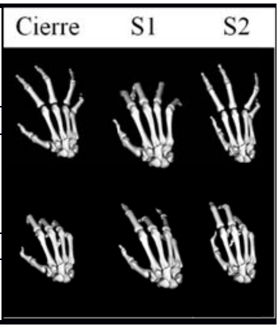
Table 6.7. Percentiles of the pathological subjects in the statistics for posture and velocity in ADL

		Position factors					Velocity factors				
		FArc	Clos	PArc	LatP	Opps	FArc	Clos	PArc	LatP	Opps
S1	Mean	<0	6	43	>100	38	>100	<0	35	<0	100
	Std Dev	<0	63	<0	24	<0	<0	83	24	79	33
	Min	96	12	89	>100	87	85	<0	<0	<0	<0
	Max	<0	6	21	90	30	68	>100	99	>100	>100
	Range	<0	56	<0	4	14	44	>100	>100	>100	>100
	Median	4	8	46	>100	29	71	13	27	21	62
	P25	1	13	65	>100	56	97	82	30	84	100
	P75	<0	17	26	>100	22	4	2	40	1	<0
S2	Mean	26	34	30	50	21	64	90	55	61	74
	Std Dev	49	>100	41	43	21	70	>100	47	69	22
	Min	34	<0	53	47	72	56	8	22	65	96
	Max	30	>100	21	51	30	97	>100	19	78	11
	Range	42	>100	10	63	33	89	99	42	62	2
	Median	17	41	30	47	18	<0	95	>100	47	93
	P25	33	19	29	29	28	19	<0	33	7	52
	P75	33	85	27	49	11	96	>100	68	84	48

The dendrograms obtained in the hierarchical cluster analyses that were performed (not shown for the sake of brevity) showed that pathological subject S1 was separated from the healthy subjects in actions 2, 4, 9, 11, 12, 15, 19, 22 and 24, especially in the last two, whereas subject S2 separated in actions 4, 14 and 15.

Lastly, Table 6.8 shows the results of the comparison between the principal components of each subject with respect to those obtained globally. The statistics of the subjects in the reference sample and the individual values for the pathological subjects are shown.

Table 6.8. Comparison of the principal components of each subject with respect to those of the reference sample

	Angles of deviation (°) between the factors of each isolated subject and those of the reference sample					% of variance explained by the factors of each subject					
	FArc	*Clos*	*PArc*	*LatP*	*Opps*	*FArc*	*Clos*	*PArc*	*LatP*	*Opps*	
Reference sample											
Minimum	8.6	11.0	20.2	15.1	14.9	18.22	10.63	8.29	7.69	7.76	
Maximum	29.9	39.2	48.2	50.8	50.6	31.09	31.89	16.03	21.92	13.41	
Mean	14.1	20.1	32.8	32.9	34.2	22.23	23.62	11.54	12.46	10.31	
Std. dev.	4.3	7.9	7.9	10.3	11.6	3.42	5.11	1.94	3.86	1.55	
Pathological Subjects											
S1	29.0	69.0	41.2	25.1	23.0	32.82	10.76	14.88	14.80	8.82	
S2	16.5	12.0	48.1	37.1	50.8	20.37	29.50	9.08	8.65	10.65	

6.4 Discussion

Although both patients had been clinically discharged, the woman (S2) was observed to exhibit normal values in terms of strength and slightly affected AROM values, whereas the man (S1) was clearly affected both in strength and in AROMs, especially in his proximal interphalangeal joints. The dexterity tests do not seem to provide significant information regarding functionality, since they do not distinguish between the pathological subjects S1 and S2, both classified as being strongly affected in gross and fine dexterity. The woman, recovered from a stroke, was capable of performing the ADL requested with a notable degree of normality, whereas the man with the injured hand, despite managing to complete all the ADL, related greater difficulty in certain tasks such as writing. These tests may be portraying an exaggerated picture for the purpose of functionality analysis. Moreover, while the test was being performed on healthy subjects it could be seen that their results are highly influenced by the person's willingness and character. Thus, there was a visible difference between those who are more nervous and competitive and those who are calmer and more relaxed, although this character trait does not imply any kind of functional disorder.

The proposed kinematic analyses provide more information than classical tests about the impact that the kinematic alterations derived from their pathology have on the performance of ADL. In the case of subject S1, large differences are observed in terms of posture and velocity (Table 6.7). The mean values for the *FArc* and *Clos* postures are lower than those of the reference sample in the ADL, while they are higher for *LatP*.

This is in accordance with the limitations produced by the injury, with a retracted posture of the hand in its relaxed position, and would also explain the differences found in the AROMs. The ranges of variability are lower than those of the reference sample, except for the factor *Clos*, which gives an idea of the loss of dexterity. The mean velocity of the factors *FArc*, *PArc* and *Opps* is higher than for the reference sample, whereas that of the factors *Clos* and *LatP* are lower. Additionally, more extreme values are observed in the factors *Clos*, *PArc* and *LatP*, which seems to indicate an abrupt transition between postures due to problems in the control over such movements. On reviewing the angles of deviation between factors in Table 6.8 for subject S1, the only factor with values outside the limits of the reference sample is the factor *Clos* (see representation of the factor Clos for the reference sample and subjects S1 and S2 in Table 6.8), thus highlighting the physical alteration generated by the injury. On the other hand, the variances explained by the components of subject S1 are within the limits of those of the reference sample, but with values higher than the mean for the factor *FArc* at the expense of the factor *Clos*, possibly due to the problems discussed for this last factor. From the dendrograms for each activity it can be seen that subject S1 moves away from normality in actions where a manipulation involving the factors *FArc* and *LatP* are required, such as writing, eating with a fork or brushing one's teeth.

In the case of Subject 2, the detailed analysis of her kinematics enables us to observe a certain degree of divergence in *Clos* with respect to the reference sample, with higher velocities and amplitudes of the postures, in contrast to the lower values of AROM recorded in the metacarpophalangeal joints for S2 in comparison to the reference sample. The recovery of the ability to flex the metacarpophalangeal joints in stroke patients is usually a costly process, as shown by the AROM values recorded for S2. Yet, the kinematic analysis indicates that she uses a greater functional range than the reference sample. This is possibly due to the fact that during rehabilitation perhaps more emphasis was placed on recovering the mobility of *Clos*, and that the patient therefore uses this movement to make up for deficiencies in other factors that have been recovered to a lesser extent, such as *PArc* or *Opps*, which have low values compared to those of the reference sample. Very extreme values are also observed in the velocities of the factor *Clos*, which can be indicative of a certain degree of difficulty in their control. The factor *LatP* presents values that are more in line with those of the reference sample, in terms of both posture and velocity. These results would be consistent with affected fine dexterity, as shown in the Purdue test. But whereas this test does not offer further information, the PCA enables us to see that the impact on the capacity to perform the ADL is relative, certain movements being affected more than others, and it can also be observed how they offset each other, in terms of postures and velocities. The values in Table 6.8 for S2 lend support to these observations, with greater dissimilarities in the factors *PArc* and *Opps* (but within the values of the reference sample), and more variance explained for the factor *Clos* at the expense of *PArc* and *Opps*. The differences observed in the dendrograms for each activity of subject S2 are possibly more a result of proprioception with respect to her lower limbs and shoulder than due to functional difficulties in the hands.

6.5 Conclusions and future developments

This study describes an approach to using dimensional reduction based on PCA as a valid objective method for the functional assessment of the human hand. The different methods proposed yield results that are in line with the classical measurements of strength, AROM and dexterity tests, but offer more detailed information about the kinematic behaviour of the subject while performing ADL. The three comparisons that have been carried out provide complementary information. A comparison of individual PCA may be the simplest to apply and interpret, and provides information about the coordination of the movements and their frequency of use. The comparison of the percentiles of the posture and velocity statistics yields more detailed information, not only about postures but also about velocities, although its interpretation is more complex. Lastly, the hierarchical cluster analysis makes it possible to detect problems that arise in performing particular activities. Hence, these methods can be used as the basis for the development of a tool to carry out an objective assessment of functionality in performing ADL, which can be used both for the assessment of the level of disability and for defining rehabilitation strategies, as well as in making clinical decisions. Certain limitations of this work must be noted before it can be applied. These limitations include the size of the reference sample and the selection of activities, which, moreover, have been guided and controlled to a large extent. The aim of this study is to serve as the starting point for the development of an open database of subjects and actions, so that it can be updated with new measurements, for both normal and pathological subjects, and with a wider variety of actions, as well as including both hands.

6.6 Acknowledgements

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Discussion & Conclusions

DISCUSSION & CONCLUSIONS

Global discussion

The results that are presented in this thesis are the culmination of a research work whose goal was to provide useful contributions to the functional assessment of the hand. Due to the format of the thesis as a compendium of articles, each one with their own identity, there are some important issues that have been treated during the development of the thesis but that either have been only slightly mentioned in the papers or that have not been reported at all. Therefore, it is worthy to provide here a global discussion linking all the results, including those poorly treated.

Chapter 1, along with a study presented in a Spanish congress (Gracia-Ibáñez et al. 2014a), have provided the evidence that at present there are no objective evaluation methods of the hand function applicable to different patient populations. From the visits performed to clinicians, I have had the chance to observe that the guidelines for the rehabilitative practice to be followed by physiotherapists are usually established by a medical rehabilitation orthopaedist, and that the criteria for ending the treatment rehabilitation is commonly based in the apreciation of no further improvements, without any specific assessment of the level of functional recovery achieved. Also, the importance of hand kinematics for hand function has been evindenced, being an objective way of providing measurable and comparable data to be used in evaluation and rehabilitation (Laffont et al. 2014; van Dokkum et al. 2014). Therefore the core of the thesis is established in the search of contributions to the functional assessment of the hand, focusing on its kinematics. As far as functionality of the hand is concerned, the field of study for this thesis is oriented to assess the ability to perform ADL, to provide a general method suitable for dependency assessment in accordance with many other works (Meiners et al. 2002; Foki et al. 2016; Brinkhorst et al. 2016) and with the widely spread physiotherapists' belief that ADL should be considered in treatments (Powell & von der Heyde 2014). The state of the art has allowed identifying the lack of agreement in the ADL considered in the different works from literature (Light et al. 1999; Light et al. 2002), which could be solved using the ICF (Lindner et al. 2010; WHO 2001) as it is the only worldwide recognized reference to assess health aspects. In all, the proposal performed in this thesis for selecting the ADL is to choose those activities within the ICF where the hand is directly involved. The identification of the most used grasps was tackled in a previous work (Vergara et al. 2014), from which the question of what are the more relevant grasps for autonomy arose when trying to use those data for improving the functional assessment. Appart from the lack of consensus on the selection criteria for ADL necessary for autonomy, the scarcity of works addressing the assessment of functionality by means of evaluating the ability to perform different types of grasp has been evidenced (Light et al. 2002; Brogardh et al. 2007), along with the scarcity of works dealing with rehabilitation strategies based on training grasps. Light et al. (Light et al. 2002) proposed a new assessment method based on evaluating the performance of 6 grasp types, by assigning a grasp type to each ADL. Their selection of ADL was based on the estimated percentage of use of each type of grasp during ADL (Sollerman & Ejeskar 1995), but they did not consider any weighting on the importance of each ADL. Therefore, the 1st experiment of the thesis was carried out with the goal of providing a rating of the relevancy of grasps types for the autonomy. Preliminary findings from this experiment were presented in a congress in Milan (Gracia-Ibáñez et al. 2015), and final results are under revision in the Journal of Hand Therapy (Gracia-Ibáñez et al, 2016b). Having this rating at disposal may answer the question whether the most relevant grasps are the most frequently used, through comparison of results with those from our previous work (Vergara et al. 2014). In the absence of data, physicians might be tempted to train those grasps of higher usage, although they do not have to be the most relevant for autonomy, according to our findings. Therefore, the data provided may be a useful reference for physiotherapists to establish rehabilitation strategies leading to improve hand function by training the most relevant grasps for functionality. The data could also be used to improve those assessment tests that currently do not consider any weighting of the importance of each grasp for autonomy. It is also revealed that grasps where thumb is in opposition to the palm and adducted (pinch, cylindrical and lumbrical) are the most relevant ones, which highlights the importance of the thumb in functionality. Moreover, the importance of each grasp type has been shown to be dependent on hand dominance as well as on whether the hands are collaborating or not, which should be considered also in recovery strategies depending on the patient situation (one/two hands affected or whether the hand affected is the dominant one or not). The rating provided could be useful not only to select the strategies for rehabilitation but also to evaluate the level of functional recovery, since being able to perform the most relevant grasps would ensure a high level of functional recovery that could be even quantified in terms of percentage. Currently, the level of recovery achieved is not usually quantified, since even when quantitative evaluation methods are used, like grasp strength or AROM achieved, there is no evidence of their exact relationship with functionality or autonomy.

The visits performed to clinicians, along with literature, have allowed me observing that measurement of AROM is the most used quantitative method of hand function. Several works have studied the inter- and intra-reliability across operators (Lewis et al. 2010; Bashardoust Tajali et al. 2016) and clinicians are recommended to standardize methods of testing (Gajdosik & Bohannon 1987). Nevertheless, it has been observed, from literature and from direct feedback of the professionals visited, that the most common way to measure AROM is goniometry (Macionis 2013), and that no standardization of the measurements is performed. This implies, for example, that posture of the rest of fingers not being measured is not always kept in the same configuration. Santello et al. (Santello et al. 1998) proved the interdependency on the flexion-extension at the MCP level, being higher as closer the fingers were. Other authors have shown other hand joints interrelations (Braido & Zhang 2004; Lin et al. 2011), produced by the mechanical and neural couplings and affecting the range of motion of hand joints (Lang & Schieber 2004). However, the interdependency of flexion-extension of the MCP joints has not been quantified up to now. Therefore, the 2nd experiment of the thesis was carried out with the goal of quantifying the interdependency of the maximal flexion-extension MCP joint angles. Preliminary findings for extension were presented in a Spanish congress (Gracia-Ibáñez et al. 2014b), and complete results for flexion and extension are presented in chapter 3, being the mean values across postures in accordance with those reported in literature. Apart from the indirect contribution to functional assessment by showing more realistic MCP AROM values depending on the posture, the most important contribution to functional assessment is providing the equations that allow the calculation of the AROM of a healthy MCP joint depending on the actual posture of the other MCP joints. These equations are valuable data for improving existing biomechanical models, avoiding non-realistic postures. Results from this study have revealed a higher dependence in extension than in flexion, which is also of interest for clinical decision-making. The pathological hands with the neural or mechanical couplings affected are not expected to follow these equations. The difference between the AROM values estimated from the use of these equations in different hand postures and the actual AROM measured could be considered in functional assessment. It may seem contradictory to say here that improved knowledge of AROM may contribute to the functional assessment, since it has been previously stated that the relationship between AROM and functionality has not been yet tested. But this is one of the most significant contributions of this thesis (chapter 5).

It is well known that a proper hand function requires both an adequate kinematic performance (Tsai et al. 2016) and using adequate gripping forces (Soler & Rizos 2006). However, given the unaffordable magnitude of the overall problem, the thesis is focused only on the kinematic aspect. The complexity of the hand, due to its high number of DoF, results in two challenging problems: recording the kinematics of the hand with accuracy, and analysing the big amout of data recorded. When planning the measurement of the hand kinematics during ADL we first used a videogrammetric technique previously developed by the group (Sancho-Bru et al. 2014), based on its good accuracy. However, during the very first set of pilot experiments it was discarded due to markers double hindrance: they interfere with a normal development of ADL and present occultation problems when performing ADL. Eight cameras are not enough to solve hiding markers problem, worsened by the small size of the segments that become in a high concentration of markers (Coupier et al. 2016). Other systems as electromagnetic devices were considered but also discarded due to the magnetic disturbance in the presence of metal components (Cescon et al. 2015). Lower accuracy has been reported in the case of kinect systems (Metcalf et al. 2013) in spite of the recent improvements. Inertial methods have been used for assessing the whole upper-limb (Carpinella et al. 2014; Lang et al. 2013), but their size makes them non-suitable for the hand, though some attempts have been made (Kortier et al. 2014). Therefore, in the research of a suitable MoCap system, the use of an instrumented glove (Cyberglove I, 18 sensors, right hand), which is at disposal of the Biomechanics & Ergonomics Group, has been tested, resulting in the most appropriate system. In fact, it is easyly portable, without hiding problems and minimun interference with the development of ADL (only some specific activities that could damage the glove like whashing hands could not be performed, but could be mimicked). Instrumented gloves have been shown to provide accurate results if detailed calibration protocols are used (Buffi et al. 2013; Eccarius et al. 2012; Griffin et al. 2000). However, such protocols are cumbersome and tiresome (Kessler et al. 1995; Eccarius et al. 2012; Buffi et al. 2014), non-suitable for pathological subjects. Fast calibration protocols proposed in literature lack also from accuracy (Buffi et al. 2014). Under this situation, the 3rd experiment of the thesis was developed in order to test the proposal of using an across-subject calibration that could provide accuracy enough for its use in functional assessment and suitable for pathological subjects, which is presented in chapter 4. Once the calibration has been performed to one glove, only a simple reference posture is required in order to record kinematics to any subject. To apply this method of calibration, care has to be taken especially in performing the closed loop motions made between index finger and the thumb in order to not exceed the linear region of the sigmoid curve between DIP and PIP flexion (Van Zwieten et al. 2015). This procedure has been shown to provide mean precision error of 4.45º. Comparison with videogrammetry has shown only slightly inferior angles in some cases, probably due to the stiffness provided by the glove. Although correlation of errors with hand length has been found, resulting errors are acceptable without hand size correction. For the use of the instrumented glove in further experiments for studying ADL, sample rate of 75 Hz is considered as appropriate according to literature, only being required frequencies over 100 Hz for sports purposes (Nowak & Hermsdorfer 2009; Imamura et al. 2007; Mapelli et al. 2012; Dinu et al. 2012). Healthy subjects as well as the pathological ones who participated in the further experiments focused on ADL have been asked about the stiffness of the glove, and have reported good level of comfortability.

By using this protocol, the 4th experiment of the thesis was carried out with two purposes: first one, studying the relationship between AROM and FROM, so as to test the goodness of using AROM measurement to assess functionality as it is currently done; and second one, the testing of PCA as a method to assess functionality. Chapter 5 provides a large quantity of directly applicable data to be used by clinicians. It is worth noting the provided tables that allow assessing the level of functional achievement from the AROM recovery. This is a contribution that has received very good acceptance feedback by the clinicians we have established contact with, who have higlighted the importance and practicity of the contribution. Data are presented globally and stratified by gender for all the hand joints except for DIP joints. For these joints, AROM could be estimated using the sigmoid curve between DIP and PIP flexion proposed in a previous work (Van Zwieten et al. 2015), which reflects the effect of the bundles of the extensor assembly. AROM data provided are in accordance with those reported in literature, although slightly smaller in some cases as in MCP joints, because of the stiffness provided by the glove. The work evidences the problems arising from the non-standardization in the measurement of AROM, as well as in the definition of CMC movements. It also provides the AROM of the palmar arching as a novelty. It is worth mentioning that, in general terms, FROM angles required are lower than AROM, thus reinforcing the use of AROM for functional assessment, but pointing out that this could result in too demanding goals for the patients in some cases. FROM data are reported in different and easy usable ways. The data provided could be used for functional assessment, rehabilitation purposes and for clinical decision-making.

Last but not least, chapter 6 shows the results of testing PCA as a feasible method to assess hand functionality. Prior to test this method in pathological subjects, it has been checked that just five synergies are enough to account for close to 74% of variance of the hand postures required for the set of representative ADL for healthy subjects recorded in the 4th experiment, which was presented in the ESB-2016 congress (Gracia-Ibáñez et al 2016a). Complete results are presented in chapter 6. Two pathological subjects have been recorded performing the same set of ADL with the same protocol than in the 4th experiment and the postures expressed in base of the five factors obtained. Three different approaches have yielded results that are in accordance with classical assessments, but providing more detailed and complementary information. The first approach consists on obtaining statistical values of centrality and dispersion both for posture and velocity, in order to identify the percentile of the pathological subject with reference to the healthy sample. The second approach implies a hierarchical cluster analysis to detect the similarity of postures and velocities in relation to the healthy sample for each activity, allowing the detection of deficiencies of pathological subjects when developing specific ADLs. Finally, the third approach is based on the comparison of synergies between the pathological subject and the healthy sample. Comparison of classical measurements as dexterity tests, AROM or grip strength with the kinematic data collected has allowed identifying that these classical evaluations tend to be conservative as far as functionality is concerned. Thus, dexterity tests as B&B test or Purdue tests may give an exaggerated evaluation of a loss of functionality. Furthermore, they do not provide a more specific idea of what kind of kinematic actions are affected by the pathology. This is a big advantage of the method presented in this thesis since it provides more detailed information about the differences between the behaviour of the pathological and the healthy hand, allowing inferring the possible causes or guiding rehabilitation.

The comparison of the kinematic data of the pathological subjects with the healthy sample in this last experiment has provided valuable and complementary information. The first approach of comparing the percentile of posture and velocity statistics in the whole set of ADL provides detailed information both on postures and velocities. However, the interpretation of the results are not straightforward as it requires the comparison of 8 statistical parameters on both postures and velocities for the five synergies (8x2x5=80 comparisons). A deeper knowledge of how all these statistics are affected by different pathologies could lead to a smaller set of parameters to be compared, improving the applicability of this method. Furthermore, applying this approach as it is presented here requires the performance of all the ADL by the pathological subject to be evaluated, which could be unfeasible in certain pathologies or with certain levels of affectation due to the pathology. This problem could be overcome if this approach is not applied globally but per activity, which would provide a detailed insight on how the hand kinematics is affected in each specific activity, although increasing the complexity of results interpretation. The second approach, which uses the hierarchical cluster analysis, is based also on comparing the same 80 parameters as does the previous one. But in this case the method provides a global comparison of the set of parameters, and it is already performed per activity. Therefore, it allows detecting problems affecting particular activities, although it is somewhat qualitative in the interpretation. The third approach of comparing indidual synergies may be the simplest to apply and interpret, providing information on movements coordination, along with their frequency of use. However, it does not consider velocities, which have been shown to present more differences between pathological and healthy subjects (first approach). Furthermore, this last approach requires the performance of the whole set of ADL by the pathological subject, which could be unfeasible in some cases, and can't be applied differenciating by activity.

Contributions

In this section just a brief explanation of the main contributions to hand assessment based on its kinematics obtained from this thesis is provided, since each chapter already contains a detailed analysis of the specific contributions made regarding the study presented in the chapter.

First, a review of the current state of hand assessment in ADL has been developed. From this review it has been possible to observe that most methods of hand function assessment are illness-specific and highly subjective. This has been also confirmed from the feedback from doctors and physiotherapist personnel who perform hand function assessments daily.

Second, a rating of the relevance of the different grasps types for the autonomy is provided. This information has not been reported up to now, and can be used in a qualitative assessment approach, to guide the strategies of clinic professionals in rehabilitation for best functional recovery.

Afterwards, equations quantifying the interdependency of maximum flexion-extension at the metacarpophalangeal level are provided (for fingers: index, middle, ring and little), with direct applicability for improvement of hand biomechanical models. More realistic AROM of the MCP joints are provided, taking into account the posture of the rest of fingers, as it has been also evidenced that hand posture while measuring

AROM is not standardized. A higher interdependence has been evidenced on extension than on flexion. Results are also valuable information to clinical staff for functional assessment, by checking abnormalities in the interdependence.

Then, an across-subject calibration protocol for instrumented gloves has been developed, which has good accuracy in anatomical joint angles obtention and best suits for functional assessment of pathological hands, since just one simple reference posture is needed.

As a fifth contribution, the relationship between AROM and hand functionality has been established through the comparison between AROM and FROM. Easy usable data is provided to evaluate the functional recovery level from the AROM recovery achieved. In general terms, FROM are lower than AROM values and are different depending on the ADL. AROM values could become into too demanding goals when used as reference for functional recovery. AROM of the palmar arching provided is a novelty.

Finally, five synergies underlying the functional kinematic behaviour of the healthy hand were identified and interpreted. By using them, a kinematics-based quantitative method to assess the hand functionality is proposed. It is objective and susceptible to be applied to different pathological populations. The method provides detailed information of the pathological kinematic behaviour and their dissimilarity with the healthy one, which could be helpful in clinical decision-making.

Limitations

Specific limitations of the results of each paper presented in this thesis are reported in the corresponding chapter. A summary with the most general ones is presented afterwards, describing the extent of the study regarding the global goal of contributing to the functional assessment of the hand.

- Functionality of the hand has been analyzed just in terms of the kinematic ability to perform ADL.
- The set of ADL considered for the analyses is not exhaustive.
- The results are limited to the dominant hand of right handed subjects in 16 hand joints, including neither the distal interphalangeal joints, nor the wrist.
- The number of subjects used as representative of the healthy hand is limited to 24, since it is a preliminary study, although with a good representativeness in age, gender

and hand size.

- Only two pathological subjects were used in the prospective study, a man with a severely injured hand and a woman recovered from stroke.

Future research

This thesis has been in fact the seed for the projects funded by the UJI (P1-1B2014-10) and the Spanish Ministry (DPI2014-52095-P), and the experiments developed have to be considered as a preliminary study in order to test the feasibility of the methods proposed as objective and general methods for assessing hand function. Given the promising results, further research will be undertaken in order to widen the extent of the studies and to test their applicabililty. Only the main and more imminent research work to be undertaken is presented here, since the goal of the thesis is so wide that a complete list of all possible future research would be too extensive.

- A higher number of subjects and ADL would be recommendable for having a more reliable kinematic characterization of the healthy hand while performing ADL. An open data base is desirable, with the possibility of adding data from more subjects and new ADL from the ICF. The database could contain all ICF activities where the hand is involved.

- The proposed methods of using PCAs as a tool to assess hand functionality (chapter 6) need to be tested and adapted to be applied on larger samples of different pathologies. Prospective analysis of data recorded in different pathologies (stroke, multiple sclerosis, cervicobrachial neuralgia, scoliosis and tendinitis, rheumatoid arthritis, post-polio syndrome and osteoarthritis in the fingers) are already being made.

- Recording of both hands should be considered in further studies, since bimanual coordination is fundamental in recovery (Metrot et al. 2013). Influence of the bimanual performance of ADL or hand dominance must be taken into consideration in functional evaluation.

- Simultaneous measurement of the wrist and hand kinematics should be addressed. This could be especially important in pathological hands since impeded movements in some joints can be partially substituted by others. The feasibility of using the instrumented glove for measuring also wrist angles should be addressed.

- Correlations between kinematic outcomes resulting of applying the prososed methodology (chapter 6) and common clinical assessments have to be studied. Data recently obtained in the research stay on stroke patients could be used for initial comparisons of the outcomes from the Fulg-Meyer test and the kinematic outcomes from the methods proposed.

- Use of the synergies found in healthy hands in implementing serious games for rehabilitation could be tested. Mimicking the required synergies underlying a healthy functional hand could be used to improve training outcomes (motion control, movement amplitude, accuracy and eye-hand coordination).

- Furthermore, as far as the rating of relevancy of grasps types, more research is convenient on incorporating the patient's perception.

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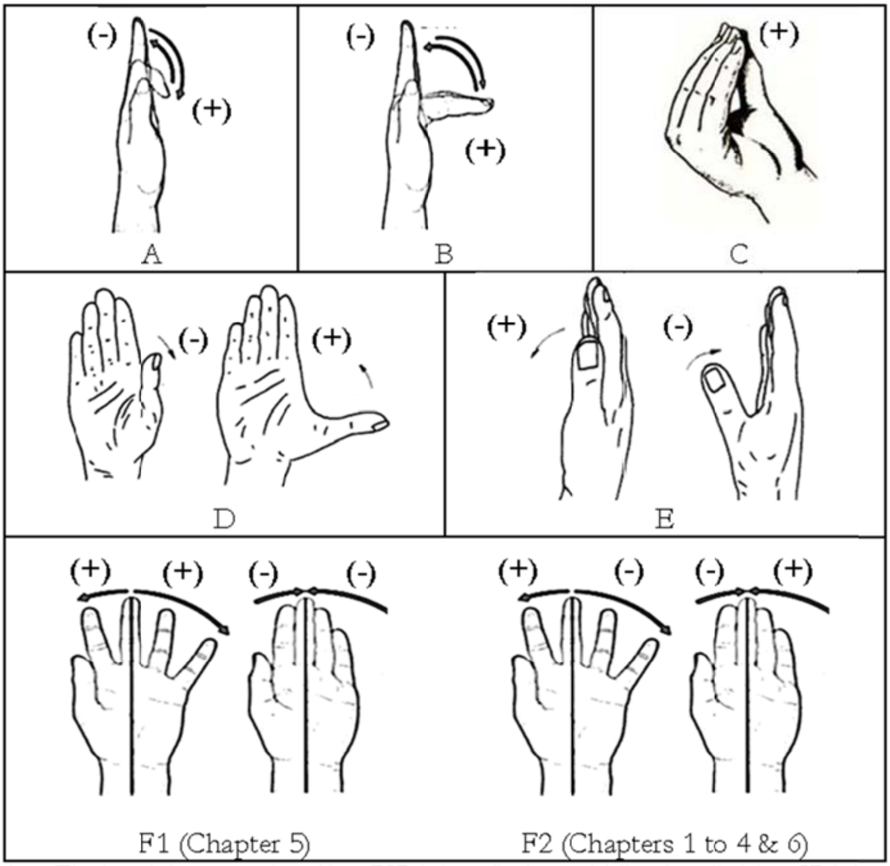
Appendix

Sign criteria for describing the joint angles of the hand is shown in Figure A1. Note that criteria for abduction of fingers is different for chapter 5.

Figure A.1 Sign criteria for hand joint angles.



A	Flexion (+) - extension (-) at PIP joints (index, middle, ring, little) & IP joint (thumb)
B	Flexion (+) - extension (-) at MCP joints (thumb, index, middle, ring, little)
C	Palmar arching
D	Flexion (+) - extension (-) at thumb CMC joint
E	Abduction (+) – Adduction (-) at thumb CMC joint
F1	Abduction (+) – Adduction (-) at MCP joints (index, ring & little respect to middle) (Chapter5)
F2	Radial deviation (+) – Ulnar deviation (-) at MCP joints (index, ring & little) (Chapters 1 to 4 & 6)