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TITLE PAGE

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Biomechanical function requirements of the wrist. Circumduction versus flexion/abduction range of motion

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ABSTRACT AND KEY TERMS

ABSTRACT

The biomechanical function of the wrist is widely assessed by measuring the range of motion (RoM) in two separate orthogonal planes: flexion-extension (FE) and radioulnar deviation (RUD). However, the two motions are coupled. The aim of this study is to compare wrist circumduction with FE and RUD RoM in terms of representativeness of the kinematic requirements for performing activities of daily living (ADL). To this end, the wrist motion of healthy participants was measured while performing maximum RoM in FE and in RUD, circumduction, and thirty-two representative ADL. Active and functional RoM (ARoM and FRoM) were computed in each plane, the evolving circumduction curves were adjusted to ellipses, and intensity maps representing the frequency of the coupling angles in ADL were plotted, both per ADL and globally for both hands. Ellipses representing different percentages of coupling angles in ADL were also plotted. Wrist circumduction fits the coupling angles measured in ADL better than ARoM or FRoM. As a novelty, quantitative data for both circumduction and the coupling angles required in ADL are provided, shedding light on the real biomechanical function requirements of the wrist. Results might be used to quantify mobility reduction and its impact on the performance of ADL, globally and per ADL, to enhance rehabilitation strategies, as well as in clinical decision-making, robotics, and prostheses.

KEY TERMS

Wrist circumduction, biomechanical function requirements.

ABBREVIATIONS

ADL	Activities of daily living
ARoM	Active range of motion
DH	Dominant hand
DoF	Degrees of freedom
F/E/FE	Flexion/Extension/Flexion-extension
FRoM	Functional Range of Motion
LH	Left hand
NDH	Non-dominant hand
RH	Right hand
{R/U/RU}D	Radial/Ulnar/Radioulnar deviation
SHFT	Sollerman Hand Function Test

1. INTRODUCTION

The simplest and commonest method to quantify the biomechanical function of the wrist is to measure the active range of motion (ARoM) in two orthogonal motion planes independently: flexion-extension (FE) and radioulnar deviation (RUD). These measurements are used to test loss of biomechanical function, since limitations in wrist movement are known to affect the ability to perform activities (Bland et al., 2008; Franko et al., 2008; Jianda et al., 2019).

The functional range of motion (FRoM), understood as the range of each movement (FE and RUD) required to perform activities of daily living (ADL) (Vasen et al., 1995), is more realistic than ARoM for function assessment. However, recording each patient’s own FRoM in clinical practice is unfeasible as it would be necessary to perform a great number of real ADL. What is feasible is setting ARoM measured in the patients against normative FRoM obtained from a representative sample of healthy participants. However, studies on wrist FRoM are scarce in the literature, and reported values are quite variable because there is no consensus on its definition and on the ADL to be considered (Brigstocke et al., 2013; Palmer et al., 1985; Ryu et al., 1991; Schuind et al., 1994). In this regard, most recent upper limb studies propose computing the FRoM as the central 90% of all joint angles employed in ADL using the 5th and 95th percentiles (Gracia-Ibáñez et al., 2017; Magermans et al., 2005).

Comparison of ranges of motion in orthogonal planes leads to a misunderstanding of the biomechanical function of the wrist. This is because, firstly, the use of FRoM or ARoM is too conservative because of the coupling between FE and RUD movements, i.e., not all combinations of angles within the FE and RUD RoM values are achievable (Ojima et al., 1991). Secondly, maximal FE angles are achieved while RUD is not in a neutral position, and vice versa (Singh et al., 2012), so that FRoM values can be higher than ARoM values measured in orthogonal planes (Brigstocke et al., 2013).

Wrist circumduction, unlike ARoM and FRoM, considers the coupling between the wrist movements. Moreover, according to previous studies (Alhay, 2018; Rawes et al., 1996; Singh et al., 2012), the use of electrogoniometers to measure it is reliable and accurate (accuracy 3º and repeatability 3.8º for uniplanar movements; accuracy 7.5% and repeatability 4% for the area of circumduction), as well as non-invasive (Akhbari et al., 2019). Ojima et al. (1991) described wrist posture as a coupling vector in the coordinate space defined by the two wrist movements (RUD, FE), with the origin in the neutral posture. They confirmed that patients perform smaller circumduction curves than healthy subjects, which shows that circumduction can be an effective indicator of dysfunction. However, the relationship between circumduction and ADL performance remains unclear. Therefore, we hypothesize that wrist circumduction might be a better biomechanical indicator to measure functional requirements for the wrist than ARoM or FRoM as regards ADL performance. If so, the ADL affected might be identified and the degree of dysfunction quantified from the knowledge of the relationship between circumduction and ADL requirements.

The analysis of the real biomechanical requirements of wrist motion in ADL involves a wide and representative set of tasks (Rainbow et al., 2016) including those demanding the most extreme wrist postures (Palmer et al., 1985) and collaborative tasks demanding the support of the non-dominant hand. Few attempts have been made to relate wrist circumduction to functionality (Dauncey et al., 2017), although with low representativeness of overall wrist function due to poor task selection.

To test our hypothesis, wrist circumduction and RoM of both hands were compared with the wrist angles required to perform a wide set of ADL. These activities were selected to represent wrist function under real dynamic conditions (Foumani et al., 2010) and were performed freely with each hand playing its role (dominant or non-dominant). Overall quantitative data of the coupling angles required in ADL that are directly applicable in clinical practice are provided as a novelty.

2. METHODS

2.1. Experiment

The experiment, approved by the University ethics committee, was conducted with eighteen healthy participants (10 men and 8 women, mean age 37 (SD 9.1) years), after giving their informed written consent. All the participants were right-handed except for one of each gender, to match the proportion of left-handed participants in the general population (Bishop et al., 1996). Twin-axis electrogoniometers (SG65 Biometrics Ltd) were used to measure (50Hz) the FE and RUD angles of both wrists (flexion and radial deviation with positive sign). The electrogoniometers were placed while the participant sat on a chair with shoulders relaxed, elbows flexed at 90º, forearms lying on the table and hands resting flat on the table, palms down, fingers and thumb close together, and forearms aligned with the middle fingers (neutral posture). They were attached firmly to the skin with double-sided adhesive tape, the two end-blocks being aligned with the forearms, one placed over the dorsum of the hand, and the second over the radius. The electrogoniometers were zeroed in this neutral posture, as in previous studies, to ensure electrogoniometer reliability and accuracy (Rawes et al., 1996; Singh et al., 2012).

2.1.1. Active Range of Motion

First, starting from the neutral posture, and with the forearm still, the participant slid his/her hand on the table to achieve maximum radial deviation (RD) and then maximum ulnar deviation (UD). Then, with the forearm resting on the table, the wrist near the edge of the table, and the hand jutting out from it, palm down, the participant went from neutral to maximum flexion (F) and then to maximum extension (E). Both RUD and FE movements were first performed with each hand independently, and subsequently with both hands simultaneously. ARoM recordings were repeated twice – before and after performing the ADL.

2.1.2. Circumduction movement

With the forearm lying on the table as in the FE ARoM measurements and secured by the instructor to avoid pronation (Ojima et al., 1991), the participant started from maximum extension, completing six radial rotations, i.e., counterclockwise for the right hand (RH), clockwise for the left hand (LH). To check for repeatability, circumduction was measured in two additional sessions with four of the participants (2 men and 2 women).

2.1.3. Activities of daily living

The movement of both wrists was recorded while carrying out 32 ADL (Figure 1) selected from the WHO's International Classification of Functioning, Disability and Health (ICF) (2001), a widely accepted reference for functional recovery. They were carefully chosen to cover the most representative activities involving the wrist, including those requiring extreme postures like fastening/unfastening a bra or getting up from a chair with armrests (Palmer et al., 1985; Schuind et al., 1994). Each participant performed each ADL once. Although we present the results of 32 ADL, each participant performed only 31 ADL: activities 24.1 (Fastening and unfastening a bra) and 24.2 (Shaving) were performed, or not, depending on the participant's gender.

Insert Figure 1

2.2. Data analysis

Laterality of participants was computed by means of the Edinburgh Handedness Inventory test (Edlin et al., 2015; Oldfield, 1971). All angles recorded were filtered with a 2nd-order, 2-way, low-pass Butterworth filter with a cut-off frequency of 5Hz.

2.2.1. Active Range of Motion

For each hand, each participant and each repetition, ARoM values (F, E, RD, UD) were computed as the maximum/minimum values from all the corresponding filtered recordings of ARoM.

Repeated measures ANOVAs were applied to ARoM values obtained before and after performing the ADL (8 ANOVAs: variables F, E, RD, UD for the dominant hand (DH) and for the non-dominant hand (NDH), factor: before/after) to check for electrogoniometer end-block displacements during test performance, i.e., their stability relative to the skeleton. In addition, as shown in Figure 1, displacements were prevented by attaching the end-blocks to the skin using adhesive tape.

2.2.2. Functional Range of Motion

Participants were recorded performing each ADL with each hand and the recordings were then resampled to 1000 frames so that all the activities had the same weight in time. Subsequently, for each participant and each hand, FE and RUD FRoM values were computed as percentiles 5 and 95 of all the angles recorded while performing all the ADL, to ensure that they guarantee the performance of 90% of all the ADL considered (Gracia-Ibáñez et al., 2017).

2.2.3. Coupling angles in circumduction: Adjusted ellipses

For each hand of each participant (and each session for the four participants who repeated circumduction after performing the ADL in two additional sessions), the envelopes of the six rotations were computed after removing outliers at the beginning or the end of the movements. Outliers were detected by representing individual trajectories. The six rotation movements presented smooth paths, except for a few starting or ending instants of the whole movement, which were considered outliers and trimmed. They affected only a few participants in the NDH, where less control can lead to these outliers. From these envelopes, ellipses were adjusted with coordinate space RUD in abscises and FE in ordinates. Root mean square errors (RMSE) of the modules of the coupling vectors at each 10º increment of the ellipse and the envelope were used to check the goodness of fit between the two curves. The parameters defining the ellipses were then computed: location of the center (O_{RUD}, O_{FE}), angle of the semi-major axis of the ellipse with the ordinates axis (phi), area, and length of semi-axes (a, b).

To test the repeatability of the circumduction ellipses for both DH and NDH, inter-session errors of the main parameters (center location, angle, and axes lengths) were computed as the square root of residual variance of an ANOVA (dependent variables: each parameter; factor: ‘participant’) using the data from the three sessions involving the four participants.

Additionally, similarity of the circumduction performed with DH and NDH was analyzed through a repeated measures ANOVA applied to each of the main parameters with the factor ‘DH/NDH’.

2.2.4. Coupling angles in ADL: Mean intensity maps

For each hand of each participant, and each of the 32 ADL, coupling angles obtained while performing each activity were represented in a 200×160 frequency matrix: rows corresponding to FE angles (-100º to 100º in intervals of 1º) and columns reflecting RUD angles (-60º to 60º in intervals of 1º). Each element of the matrix contained the frequency with which the given wrist posture was used while performing the activity. Data used to compute the frequency matrix were resampled as for FRoM values. Finally, mean matrices across activities and participants were computed for both DH and NDH, and plotted as intensity maps.

2.2.5. Biomechanical function of the wrist through ARoM, FRoM, and circumduction

For each hand, mean ARoM and mean FRoM values were obtained across participants, together with mean circumduction ellipses. These ellipses were obtained from the mean envelope (computed as the mean coupling vectors at each 10º of the participant's envelopes). Parameters of both mean ellipses (DH and NDH) were computed, along with the RMSE fit values.

Mean ARoM, FRoM, and ellipses were superposed on the mean intensity maps for both DH and NDH in order to analyze their representativeness as regards ADL performance. In addition, image-processing techniques were applied to the intensity maps to generate compact areas covering 90% and 95% of the wrist coupling angles involved in performing the ADL, which were also drawn superposed on the mean intensity maps. Moreover, ellipses adjusted to compact areas covering different percentages of the wrist coupling angles required to perform the ADL were computed and represented, and their characteristic parameters were listed. The percentages presented are 95% and 90%, which can be considered to represent full functionality, and 70% and 50%, which made it possible to infer what level of reduced circumduction could prevent patients from performing the ADL.

2.2.6. Requirements per activity: Intensity maps for each ADL

To gain better knowledge of the specific requirements of each ADL, mean intensity maps were also obtained for each activity across participants and plotted superposed on the mean circumduction ellipses for both DH and NDH. For a better understanding of these maps, the role of each hand (DH/NDH) in each activity was analyzed for all the participants. To check whether individual behavior matches the mean observations, intensity maps were also represented per participant, with their ARoM and FRoM values, together with adjusted circumduction ellipses.

3. RESULTS

3.1.1. Active and Functional Range of Motion: ARoM and FRoM values obtained

The repeated measures ANOVA showed no significant differences ($p<0.05$) between the ARoM before and after performing the ADL, thereby confirming that the goniometer block-ends had not moved during the experiment. For each participant, the ARoM for subsequent analyses was the average of the two values. Table 1 shows descriptive statistics of ARoM and FRoM values for both DH and NDH.

Insert Table 1

3.1.2. Coupling angles in circumduction: Adjusted ellipses

Table 2 shows descriptive statistics of the parameters of the ellipses of both DH and NDH. The low RSME values obtained indicate a good fit of the ellipses to the circumduction movement.

Insert Table 2

Table 3 shows inter-session errors (residual errors from the ANOVAs) of the main parameters. Errors are low and similar between DH and NDH.

Insert Table 3

The repeated measures ANOVA performed to check for differences between the ellipse parameters of DH and NDH only showed significant differences ($p<0.01$) for the center location. We can infer that there are no big differences in the size and shape of the DH/NDH ellipses, except for the center location, which may be due to differences in the neutral posture, but also to differences in the location of the wrist rotation center depending on hand dominance, as reported in previous studies (Salvia et al., 2000).

3.1.3. Mean intensity maps and biomechanical function of the wrist through ARoM, FRoM, and circumduction

Figure 2 (a) & (b) show the mean intensity maps for both NDH and DH, respectively, along with mean ARoM, FRoM, circumduction ellipses, and compact areas covering 90% and 95% of the coupling angles of the wrist required to perform ADL. This allows a graphical assessment of the goodness of using wrist circumduction instead of ARoM or FRoM measurements as a biomechanical indicator. Figure 2 (c) & (d) show the same intensity maps and circumduction ellipses, but superposed with the ellipses adjusted to 95%, 90%, 70% and 50% of the ADL. Hence, the level of impact of a reduced circumduction on ADL performance can also be inferred graphically. Table 4 provides the parameters (center position, angle, area, axes lengths, and RSME) of the mean circumduction ellipses of the DH and NDH, and the ellipses covering different percentages of all the ADL. Therefore, quantitative data are provided.

Insert Table 4

Insert Figure 2

3.1.4. Requirements per activity: Intensity maps for each ADL

Appendix A provides intensity maps per ADL across participants with the mean circumduction ellipses for both DH and NDH superposed (Figure A) and a description of the actions performed by each hand for each activity (Table A) for a better understanding. In addition, Appendix B provides intensity maps per participant with individual ARoM and FRoM values and adjusted circumduction ellipses (Figure B).

4. DISCUSSION

4.1.1. Active and Functional Range of Motion: ARoM and FRoM values obtained

The ARoM values obtained are in accordance with the literature for healthy participants (Boone and Azen, 1979; Brigstocke et al., 2013; Brumfield and Champoux, 1984; Palmer et al., 1985; Ryu et al., 1991; Schuind et al., 1994). Similarly, the FRoM values for the DH are of same order of magnitude as in the literature (Brigstocke et al., 2013; Brumfield and Champoux, 1984; Palmer et al., 1985; Ryu et al., 1991; Schuind et al., 1994), but in this case they should be compared with caution because of the differences in the activities considered and the way the FRoM were computed. As a novelty, FRoM values are also reported for the NDH, values being similar to those required for the DH although the role played by each hand was different in many tasks (see Appendix A).

4.1.2. Coupling angles in circumduction: Adjusted ellipses

The circumduction movement observations also match data in the literature, with similar areas of the evolving curve (Gehrmann et al., 2008; Ojima et al., 1991; Rawes et al., 1996) and also for the slight inclination of the ellipse (Ojima et al., 1991; Salvia et al., 2000), which would be in accordance with the dart-throwing axis (from radial-extension to cubital-flexion) observed in previous studies (Crisco et al., 2011). The way circumduction is performed (rotation sense, repetitions, etc.) or the prevention of pronation can affect the area or inclination (Rawes et al., 1996; Singh et al., 2012), which may be the causes, along with the ellipse fit performed, of the differences with respect to values provided previously (Dauncey et al., 2017).

Very few previous studies have provided the parameters defining the adjusted circumduction ellipses (Dauncey et al., 2017; Singh et al., 2012). Ellipse parameters may help quantify the circumduction movement, thus allowing its use as a range of motion indicator. In this work, these parameters are provided, and are also perfectly reproducible because we provide details of the way circumduction is performed following recommendations (Gehrmann et al., 2008; Ojima et al., 1991; Salvia et al., 2000), and due to the way ellipses are adjusted.

4.1.3. Biomechanical function of the wrist through ARoM, FRoM, and circumduction

The circumduction ellipses obtained for both hands remain within the FE ARoM limits (Figure 2 a & b), with extreme values being slightly lower than the ARoM limits because of the softening effect when performing the movements. However, the ellipses exceed the RUD ARoM limits because the extensor muscles acting when extending the wrist during radial circumduction favor abduction, and the flexor muscles acting during flexion favor adduction (Carol A. Oatis, 2009).

ARoM, FRoM, and circumduction ellipses obtained should be compared with the wrist angles required to perform real daily tasks to check their performance as indicators of biomechanical function. Herein, wrist requirements (kinematics) have been recorded in a wide set of representative real ADL, including those that call for more extreme postures, so as to provide reliable data with which to assess wrist function (Palmer et al., 1985). Moreover, the activities were performed with both hands, each of them playing its role. Frequency maps from this representative set of ADL (intensity maps in Figure 2) are different for DH and NDH, depending on the role played by each hand in performing the ADL. The area with the highest frequency of use (darkest zone) for the DH corresponds to an extended and slightly ulnar-deviated posture during ADL performance, which is consistent with previous studies (Clarkson, 2012; Ryu et al., 1991). The highest frequency of use for the NDH corresponds to a more centered posture regarding RUD, maybe in part as a result of manipulation with products arranged for right-handed participants (closer to the right hand).

Figure 2 a & b confirm circumduction through the adjusted ellipse as a better indicator of biomechanical function than ARoM or FRoM values. The area within the FE and RUD ARoM limits is too conservative for function purposes, because it contains a large zone of coupling angles that are not used during ADL performance and may even be non-achievable in real coupling movements. The rectangular area defined by the FRoMs is smaller and centered in the zone of highest frequency of use in ADL. However, it does not cover the compact area that represents 90% of ADL. Conversely, the circumduction curve defines an area that contains only feasible wrist coupling angles, including the areas representing 90% and 95% of ADL. In fact, most of the coupling angles used in the different ADL are within the circumduction ellipses, except for a few pixels corresponding to extreme postures used in specific activities such as getting up from a chair with armrests (forced posture of the wrist when pushing on the chair) or fastening a bra (extreme requirement for the wrist) (see Appendix A). The center of the ellipse is in zones with a high frequency of use in both hands. Notwithstanding, free circumduction covers an area of high flexion and ulnar deviation not used in ADL, in accordance with the reduction in the circumduction ellipse in this area (Gehrmann et al., 2008) when circumduction is performed while grasping a cylinder. Perhaps circumduction while grasping a cylinder could be considered in future research to improve the fit of the circumduction ellipse to the biomechanical function requirements.

4.1.4. Clinical applicability of the results obtained

Comparison of the circumduction ellipse of a pathological hand with that of a healthy hand might provide an indicator of compromised wrist mobility, since patients with illness/injuries perform significantly smaller circumduction movements than healthy participants (Ojima et al., 1991; Rawes et al., 1996). In patients with both hands affected, mobility reduction could be assessed with the mean data of healthy participants reported in Table 4, and the resulting loss of biomechanical function (in terms of performance of real ADL) by comparing the patient's circumduction ellipse with those corresponding to 95%, 90%, 70% and 50% of ADL reported (Figure 2 (c) & (d) and Table 4). Clinicians might assess the overall impact on functionality arising from the kinematic reduction by comparing the patient's circumduction ellipse against the normative ellipses for healthy populations (Figure 2 (c) & (d)). For example, if the 70% ellipse is the largest fully contained inside the patient's ellipse, then the estimated global impact would be a reduction of about 30% of ADL. Also, specific information about which coupling angles need to be recovered to restore hand function can be obtained by identifying which areas of the normative ellipses are not reached by the patient. Furthermore, the clinician can identify which specific actions will be particularly hindered by setting the patient's ellipse against the intensity maps reported in Appendix A.

4.1.5. Requirements per activity: Intensity maps for each ADL

Intensity maps and circumduction ellipses per ADL are available in Appendix A to provide an in-depth idea of wrist motion requirements for each hand (DH and NDH) in each real activity measured, each of them playing its role, along with the frequency of use of each hand in each action. They may help to identify which specific activities can be hindered by a reduction in circumduction because of wrist impairment. In addition, the intensity maps per participant confirm that the conclusions observed from the mean values are also applicable per participant. A certain degree of variability can be found between ellipses from different participants, but only a few of them presented differences in area and inclination of the ellipses between DH and NDH. This implies that, generally speaking, for patients with only one wrist affected, comparison of wrist circumduction can be performed against that of the non-affected hand. It can then be compared with the mean intensity map.

5. CONCLUSION

In conclusion, this work reveals the circumduction ellipse as a better method for adjusting range of motion to real biomechanical requirements of ADL for the wrist than applying ARoM or FRoM in two different planes disregarding coupling angles, while also providing valuable overall data that could be applied directly in rehabilitation (Zhang et al., 2018), in clinical practice, in prostheses or in robotics. Moreover, the information reported in the Appendix A allows a deeper exploration of the kinematic requirements of the wrist in each of the ADL reported.

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Conflict of interest statement

The authors declare that they have no conflict of interest, financial or otherwise.

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FIGURE LEGENDS

Figure 1: ADL selected from the WHO's ICF as representative of wrist movements in ADL.

Figure 2: Mean (across participants) intensity map with the mean circumduction ellipse (blue) – obtained from the mean envelope, computed as the mean coupling vectors at each 10º of the participant's envelopes – along with: (a) & (b) the mean ARoM (blue lines) and FRoM (red dashed lines) values, as well as limits of areas covering 90% of the ADL (red) and 95% of ADL (green); (c) & (d) the ellipses adjusted to 95% (green), 90% (red), 70% (cyan) and 50% (yellow) of all ADL. RUD (º) in abscises (RD positive) and FE (º) in ordinates (F positive).

Table 1

	ARoM (º)								FRoM (º)							
	Non-dominant hand				Dominant hand				Non-dominant hand				Dominant hand			
	F	E	RD	UD	F	E	RD	UD	p95 FE	p5 FE	p95 RUD	p5 RUD	p95 FE	p5 FE	p95 RUD	p5 RUD
Mean	76.8	-85.2	29.5	-35.0	77.6	-79.5	27.8	-33.4	14.2	-44.1	19.5	-16.6	19.8	-44.4	16.6	-20.3
SD	7.9	10.9	5.9	6.1	6.9	9.9	6.1	5.2	6.5	5.8	7.8	5.8	8.9	7.0	6.7	4.0
Min	63.7	-109.9	16.8	-45.2	65.7	-93.5	15.0	-42.4	4.1	-54.4	8.0	-24.0	4.9	-58.6	7.4	-26.2
Max	95.5	-63.9	41.2	-24.3	94.7	-63.2	38.6	-23.4	30.3	-34.7	35.5	-7.3	38.1	-32.4	37.0	-12.9

Descriptive statistics for ARoM and FRoM values. F and RD considered to be positive.

Table 2

	Non-dominant Hand							Dominant Hand						
	O_{RUD} (º)	O_{FE} (º)	Phi (º)	Area (ºº)	a (º)	b (º)	RMSE (º)	O_{RUD} (º)	O_{FE} (º)	Phi (º)	Area (ºº)	a (º)	b (º)	RMSE (º)
Min	-16.2	-19.3	-33.6	6397.2	31.1	62.6	1.1	-16.1	-11.2	-25.9	5865.7	30.0	62.0	1.2
Max	8.9	11.2	3.5	12977.9	45.1	93.5	5.3	9.1	9.5	-1.4	10538.0	39.7	93.5	4.7
Mean	-2.3	-7.4	-12.9	9122.0	36.9	78.0	3.3	-8.1	-2.0	-13.1	8389.5	35.0	75.9	2.8
SD	6.2	8.7	10.7	1898.9	4.0	9.3	1.2	6.8	5.7	6.5	1463.3	3.0	8.8	1.1

Descriptive statistics of adjusted ellipses (all participants): center position (O_{RUD} in abscises and O_{FE} in ordinates), angle between semi-major axis and ordinates (phi), area, semi-axes length (a, b), RSME.

Table 3

	O_{RUD} (°)	O_{FE} (°)	Phi (°)	a (°)	b (°)
Dominant	3.7	5.0	5.4	3.0	7.9
Non-Dominant	4.1	3.6	6.9	3.2	7.0

Inter-session error for each characteristic of the ellipses: center position (O_{RUD} in abscises and O_{FE} in ordinates), angle between semi-major axis and ordinates (phi), semi-axes length (a, b).

Table 4

		Non-dominant Hand							Dominant Hand						
		O_{RUD} (°)	O_{FE} (°)	Phi (°)	Area (°°)	a (°)	b (°)	RSME (°)	O_{RUD} (°)	O_{FE} (°)	Phi (°)	Area (°°)	a (°)	b (°)	RSME (°)
Mean circumduction ellipse		-2.1	-7.7	-11.5	8686	37.1	74.5	2.1	-8.2	-1.8	-13.2	8039	35.0	73.2	1.5
Ellipses covering different % of ADL	95%	1.6	-14.1	1.2	4896	32.3	48.2	-	-0.8	-12.0	2.92	5072	30.0	53.9	-
	90%	1.2	-16.2	1.3	3304	26.6	39.6	-	-1.6	-12.2	3.1	3756	26.1	45.8	-
	70%	1.8	-13.8	7.7	1266	15.4	26.2	-	-2.1	-13.1	6.72	1542	16.0	30.7	-
	50%	3.2	-7.0	16.8	533	12.5	13.6	-	0.1	-12.4	17.0	754	10.8	22.1	-

Characteristics of the mean circumduction ellipse and for the ellipses covering different percentages of ADL. Common characteristics: center position (O_{RUD} in abscises and O_{FE} in ordinates), angle between semi-major axis and ordinates (phi), area, semi-axes length (a,b). The goodness of fit for the mean circumduction ellipses is provided through RSME values.

Figure 1

A1. Reading

A2. Writing

A3. Dialing a phone number

A4. Handling coins and wallet cards

A5. Cutting with a knife

A6. Eating with fork

A7. Eating soup

A8. Pouring water from a jug

A9. Pouring water from a bottle

A10. Drinking water

A11. Getting a shower

A12. Putting on shirt

A13. Fastening and undoing 3 buttons

A14. Putting on pants

A15. Putting on shoe and tying laces

A16. Getting up on chair with armrests

A17. Washing dishes

A18. Wring a cleaning cloth

A19. Opening and closing a tap

A20. Washing and drying your hands

A21. Opening a toothpaste and putting paste in brush

A22. Brushing teeth

A23. Combing the hair

A24.1. Fastening and unfastening bra (women)

A24.2. Shaving (men)

A25. Lifting a shopping bag and taking out products

A26. Stirring with a spoon

A27. Opening a jar

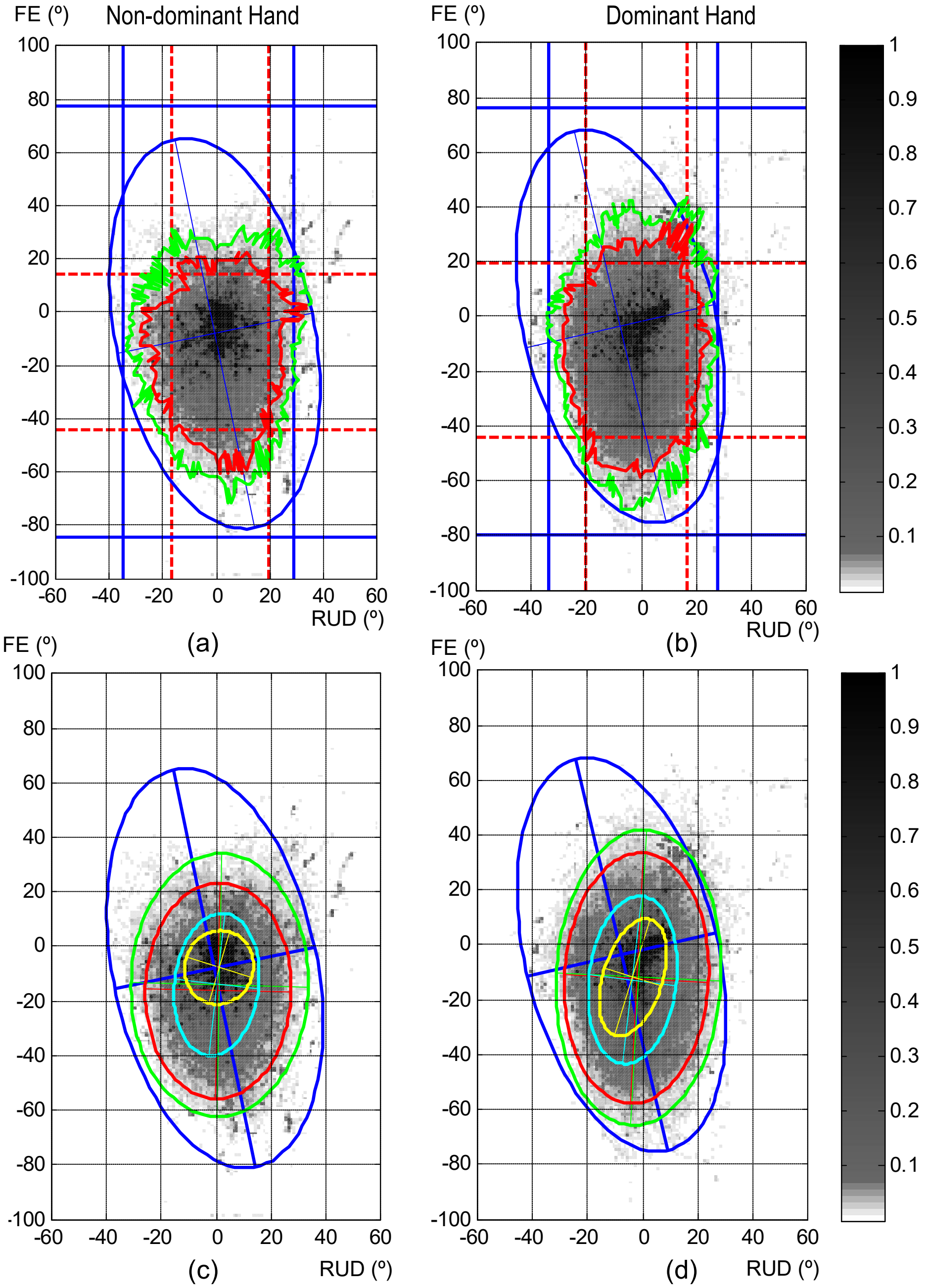
A28. Opening a can

A29. Opening door handle

A30. Opening with key

A31. Throwing a tennis ball

Figure 2


FE (º)
Non-dominant Hand
FE (º)
Dominant Hand
100
80
60
40
20
0
-20
-40
-60
-80
-100
-60
-40
-20
0
20
40
60
RUD (º)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
(a)
(b)
(c)
(d)

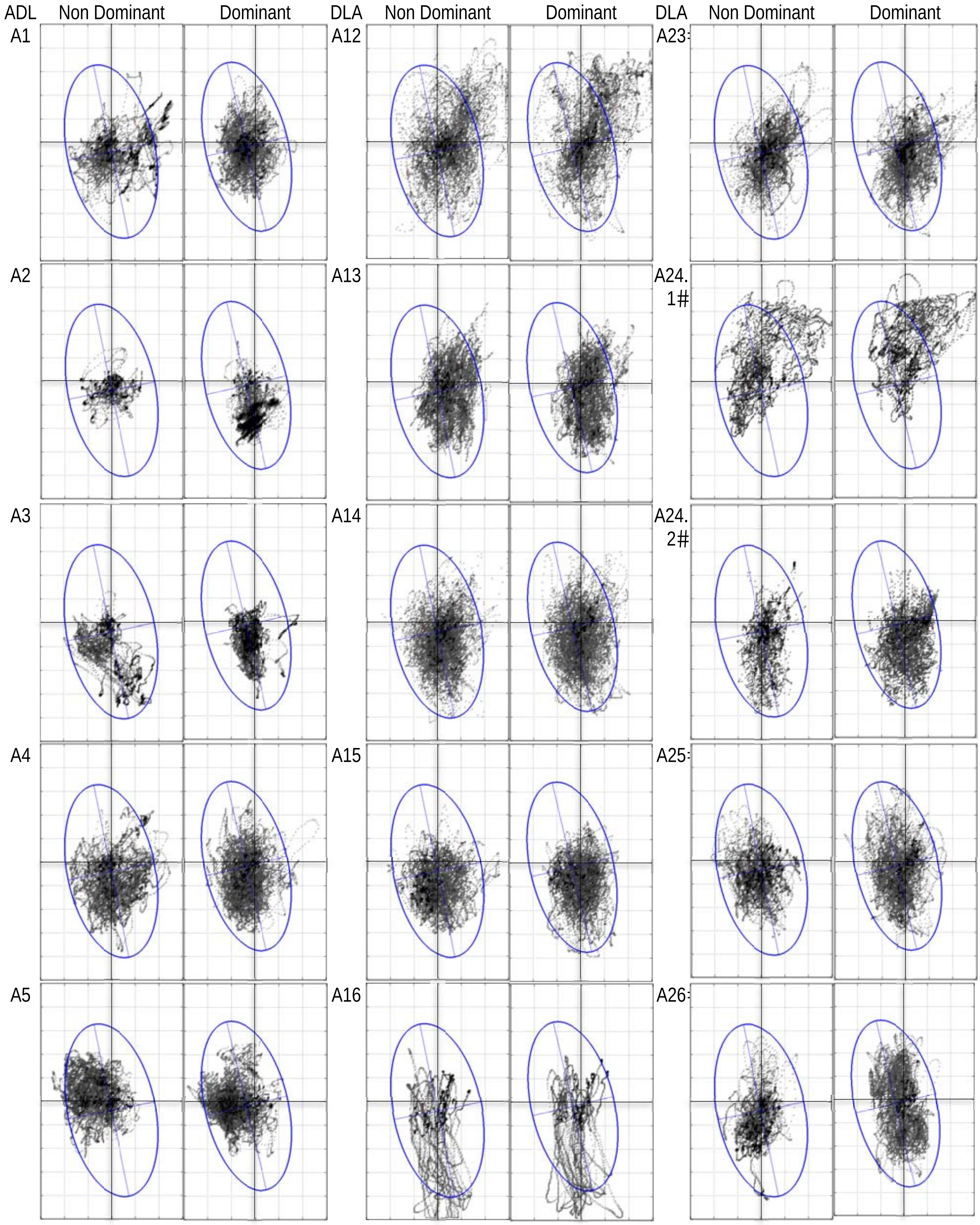
Appendix A

Figure A shows frequency of coupling angles, through intensity maps across subjects, in each of the real ADL measured. For a better understanding of these plots, Table A reports the frequency of use of DH or NDH for each action among subjects. Axes labels are omitted for clarity but each plot has RUD (°) in abscises (RD positive) from -60° to 60° and FE (°) in ordinates (F positive) from -100 to 100°.

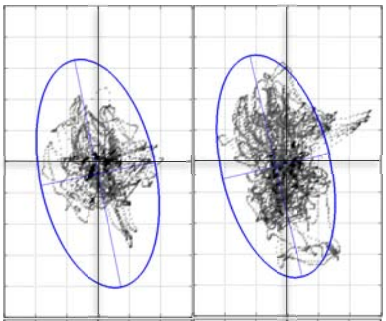
Note that:

- Most coupling angles used during the ADL fall within the mean circumduction ellipse, except for some areas in a few activities.
- Most activities present the darkest areas (highest frequency of use) quite near the center and slightly in extension.
- Requirements of coupling angles are quite different among activities: some show concentrated areas (e.g. A2-writing) and others scattered dots (e.g. A14-putting on trousers) or paths (A16- getting up from a chair with armrests).
- Different performance patterns can be identified in Table A, depending on the role played by each hand: some activities were always performed using the subject's DH, while others were always performed with the right hand.
- The joint analysis of Table A and Figure A may help identifying real joint angle range requirements for the different activities: the dispersion observed in coupling angles is due to the requirements of the actions performed by each hand, which in some cases is unique but in other cases is a mixture of actions due to the different actions performed by each subject.

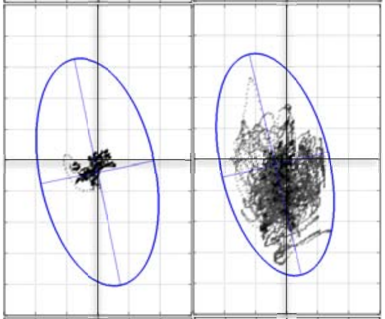
Figure A


ADL
Non Dominant
Dominant
DLA
Non Dominant
Dominant
DLA
Non Dominant
Dominant
A1
A12
A23
A2
A13
A24.1#
A3
A14
A24.2#
A4
A15
A25
A5
A16
A26

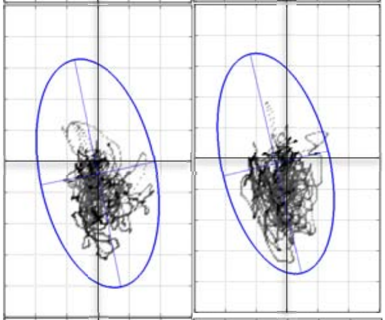
A6



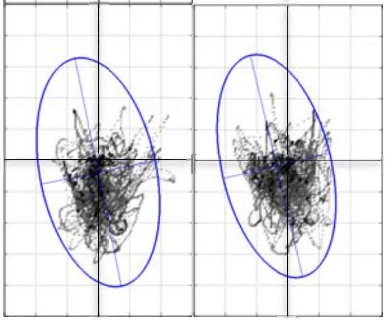
A7



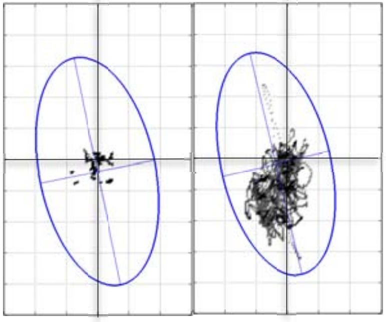
A8



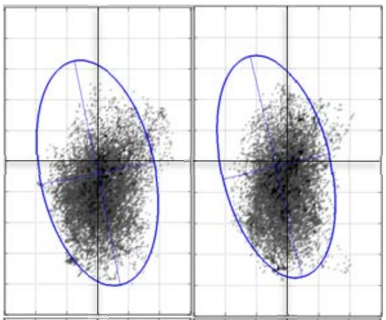
A9



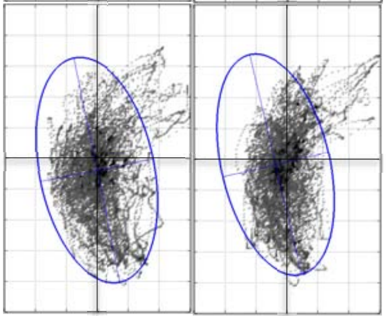
A10



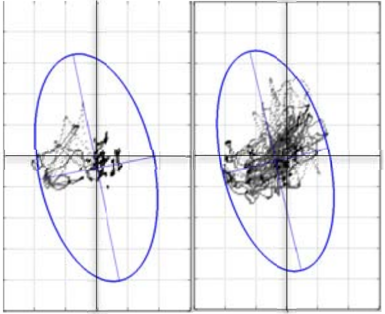
A17



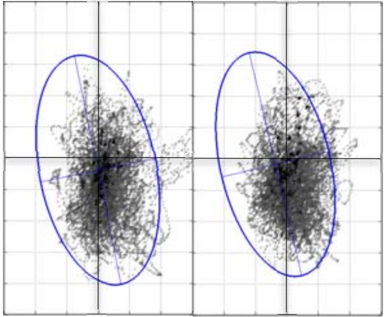
A18



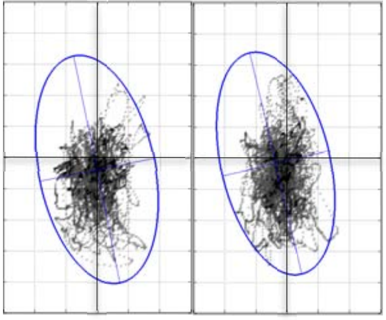
A19



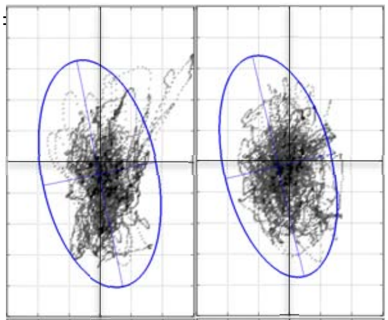
A20



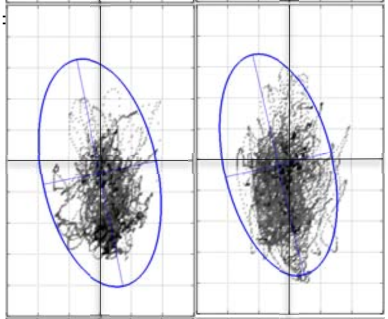
A21



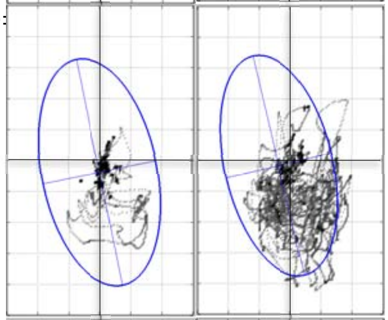
A27



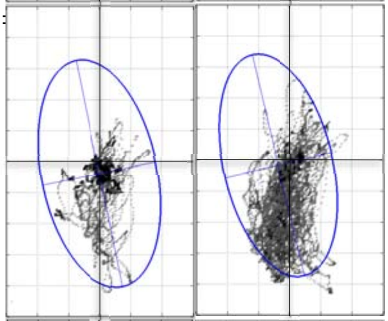
A28



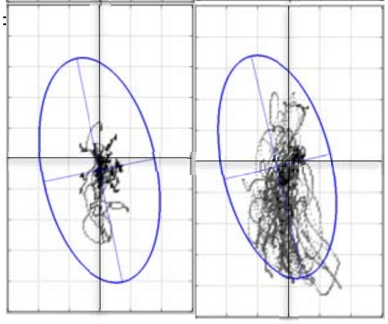
A29



A30



A31



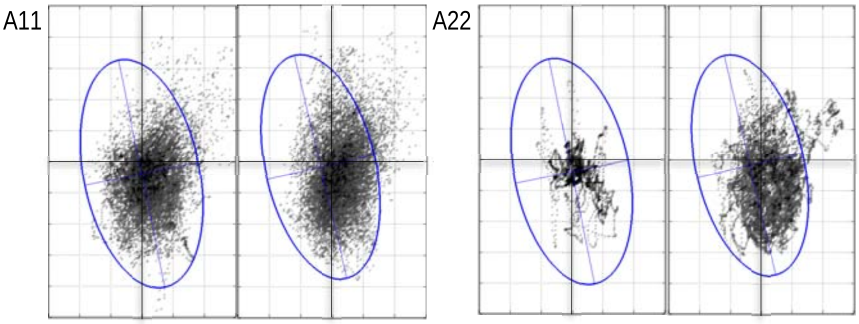


Figure A: Mean (across subjects) intensity maps for each activity along with mean circumduction ellipses (dark blue).

Table A

Id.	Activity	Action performed most frequently by DH	% subjects performing it with DH	Action performed most frequently by NDH	% subjects performing it with NDH
A1	Reading	Turning pages	89%	Holding the book	89%
A2	Writing	Writing	100%	Keeping the paper still	100%
A3	Dialing a phone number	Dialing a phone number (*)	89%	Holding the phone	89%
A4	Handling coins and cards in a wallet	Handling coins and cards in a wallet, opening and closing wallet	94%	Holding the wallet	94%
A5	Cutting with a knife	Using the knife for cutting (*)	89%	Using the fork to keep the meat still	89%
A6	Eating with a fork	Sticking the fork into the food then lifting it to the mouth	67%	Hand lying on the table	67%
A7	Eating soup	Using a spoon to eat soup	100%	Hand lying on the table Hand holding the plate	94% 6%
A8	Pouring water from a jug	Holding the jug for pouring the water	89%	Holding the mug (**) Hand lying on the table	72% 17%
A9	Opening a bottle and pouring water from it	Turning the top Holding the glass while pouring water	89% 56%	Holding the bottle firmly while opening it Holding the bottle to pour the water	89% 56%
A10	Drinking water	Holding the glass for drinking	100%	Hand lying on the table	100%
A11	Having a shower	Handling bottles (for pouring body soap and shampoo), sponge and shower head (*)	89%	Supporting the action when necessary	89%
A17	Washing dishes	Handling bottle for pouring soap Scrubbing dishes with a sponge	67% 94%	Holding the sponge while pouring Holding the dishes	67% 94%
A19	Opening and closing a tap	Opening and closing the tap	83%	Arm relaxed alongside the body in a standing position	83%
A21	Opening tube of toothpaste and putting paste on toothbrush	Turning the top to open the tube of toothpaste Putting paste on toothbrush	94% 56%	Holding the tube firmly while opening it Holding the toothbrush firmly while putting toothpaste on it	94% 56%
A22	Brushing teeth	Brushing teeth (100%)	100%	Arm relaxed, elbow at 90º, body in a standing position	100%
A23	Combing one's hair	Taking a comb out of a drawer, combing one's hair and putting it back in the drawer.	94%	Opening and closing drawer	94%
A24.2	Shaving	Opening a bottle, putting shaving foam on the other hand, shaving, One left-handed subject used both.	100%	Supporting the action when necessary (until shaving starts)	100%
A25	Lifting a shopping bag and taking out products	Lifting shopping bag from the floor (*) Taking out products and putting them on the table	89% 72%	Hand relaxed, not taking part in any action Supporting action grasping the bag	89% 72%

A26	Stirring with a spoon	Grasping the spoon Stirring	94% 100%	Grasping the bowl Holding the bowl firmly while stirring	94% 100%
A27	Opening a jar	Grasping the jar, turning the lid to open it and leave it on the table	94%	Holding the jar firmly while opening it	94%
A28	Opening a tin	Grasping the tin, opening it and leaving it on the table	89%	Holding the tin firmly while opening it	89%
A29	Turning a door handle	Opening the door using a door handle (*)	89%	Arm relaxed alongside the body in a standing position	89%
A30	Opening with a key	Grasping the key, turning it to open and close and returning it to its original position	89%	Arm relaxed alongside the body in a standing position (**) Holding the handle	78% 11%
A31	Throwing a tennis ball	Grasping the ball and throwing it	100%	Arm relaxed alongside the body in a standing position	100%

Table A: Most frequent actions performed by each hand (DH/NDH) in each activity. Actions not presented (A12 to A16, A18, A20 and A24.1) are collaborative actions, where both hands are used for the same action.

(*) Actions where all the subjects performed the action with their right hand, i.e. only the two left-handed subjects performed it with their NDH

(**) Actions performed by DH when the actions performed by each hand are reversed.

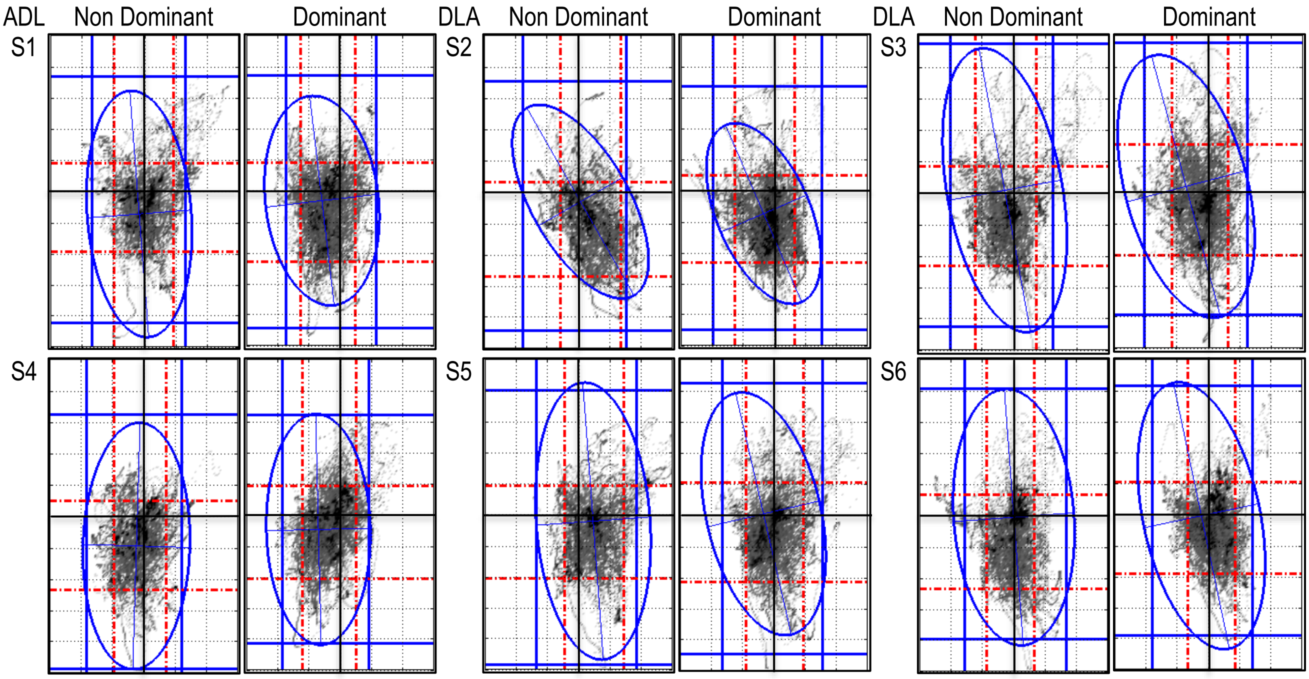
Appendix B

Figure B shows frequency of coupling angles, through intensity maps per subject performing all the ADL recorded along with their wrist circumduction fitted ellipse and their ARoM and FRom. Axes labelling are omitted for clarity but each plot has RUD (º) in abscises (RD positive) from -60º to 60º and FE (º) in ordinates (F positive) from -100 to 100º.

Note that:

- All the conclusions on the paper for the mean values are applicable for each subject individually.
- For patients with only one wrist affected, wrist circumduction ellipse should be better obtained from the non-dominant hand. Then it could be compared with the mean intensity map.

Figure B



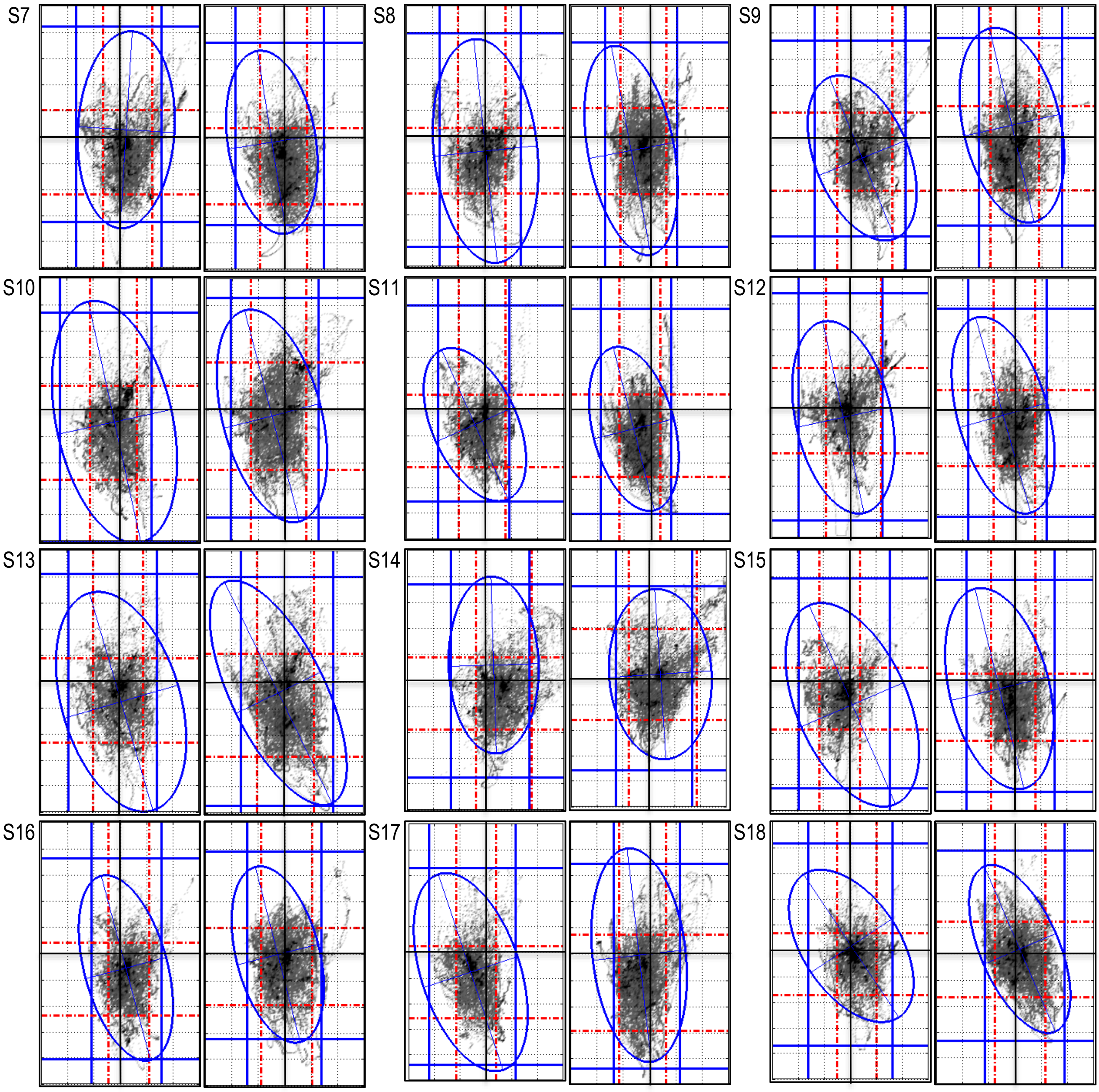


Figure B: Intensity maps per subject with their ARoM (dark blue lines) and FRoM (red lines) values, together with adjusted circumduction ellipses (dark blue).