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Brief Report

Application of the Coupling Angle to Investigate Upper Limb Interjoint Coordination After Stroke

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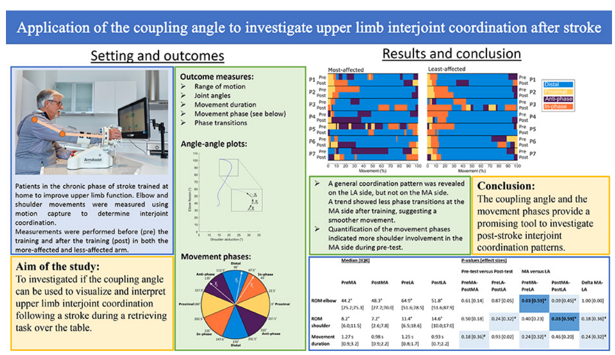
HIGHLIGHTS

- Coupling angle was firstly used to investigate upper limb movements after stroke.
- The coupling angle is an easy tool to visualize interjoint movement patterns.
- Elbow flexion and shoulder abduction ROM were smaller in the most affected arm.
- More phase transitions were observed in the most affected arm.

GRAPHICAL ABSTRACT



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ABSTRACT

Objective: Interjoint coordination after stroke is affected, which limits the use of the upper limb. Current methods to determine interjoint coordination lack the ability to visualize and quantify the movement. Therefore we investigated if the coupling angle can be used to visualize and interpret upper limb interjoint coordination following a stroke.
Methods: Seven chronic stroke patients trained six weeks with an assistive home-training system (MERLIN). Kinematic outcomes, i.e. elbow and shoulder range of motion, movement duration, and angle-angle plots were determined in a retrieving task. Interjoint coordination between elbow flexion and shoulder abduction angles was expressed as the coupling angle phases and the number of phase transitions: proximal/distal joint leading phase, in-phase and anti-phase. Comparisons were made within sides: pre-test versus post-test, and between sides: most-affected (MA) versus least-affected (LA).
Results: Smaller elbow flexion angles were found PreMA versus PreLA, and smaller shoulder abduction angles in PostMA versus PostLA. A general coordination pattern was revealed on the LA side, but not on the MA side. A trend showed less phase transitions at the MA side after training, suggesting a smoother movement. Quantification of the movement phases indicated more involvement of the shoulder joint involvement in the MA side during pre-test. After training, these differences were not apparent, which might reveal an increased independent control of the elbow joint.
Conclusions: The coupling angle and the movement phases provide a promising tool to investigate post-stroke interjoint coordination patterns.
Significance: A new visualisation of the interjoint coordination may benefit rehabilitation of stroke survivors.

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Registration: This trial was registered at the Netherlands Trial Register (NL7535) https://www.trialregister.nl/trial/7535.

1. Introduction

Estimating upper limb interjoint coordination in stroke patients can help quantify the impact of this condition on the execution of daily tasks. Upper limb interjoint coordination has previously been estimated using correlation coefficients [1–3] or the continuous relative phase [4,5]. However, the correlation coefficient, being a single value, does not offer a temporal representation of how interjoint coordination changes during a movement. At the same time, the congruent interpretation of the continuous relative phase is hampered by the number of different computation techniques so far proposed [6]. To overcome these shortcomings, we propose the coupling angle as a metric to consistently quantify and continuously visualize interjoint coordination post-stroke.

Shortly after a stroke, joint coupling limits upper limb performance during daily tasks such as reaching and retrieving [7]. Movements tend to be divided into smaller, partitioned segments [3,8]. Smoothness is also affected, with more changes between elbow and shoulder leading phases occurring in severely affected patients due to the presence of pathological synergies [9]. Robot-assisted training has shown improved smoothness and reduced segmentation [2], but not significant changes in synergistic movements [10]. The coordinative temporal pattern in a retrieving movement after a stroke and whether training using an assistive device affects this pattern, have not been investigated yet.

In this feasibility study, we investigated if the coupling angle could be used to visualize and interpret upper limb interjoint coordination. Consequently, we examined shoulder-elbow coordination of stroke survivors before and after a 6-week home training program, using an assistive training device. We expect kinematic changes (smaller shoulder abduction, increased elbow range of motion (RoM) and shorter movement duration), and a smaller number of phase transitions after the training, revealed by changes in the coupling angle.

2. Material and methods

2.1. Intervention

This research was part of the MERLIN study [11]. Adults with a first incidence of unilateral stroke more than six months ago, but within the past three years, with volitional finger extension and shoulder movement consented to participate (METc 2019/189). Exclusion criteria were: rheumatic, orthopaedic, or neurological disorders affecting the upper limbs, depression, or currently receiving arm/hand therapy.

MERLIN consisted of an assistive training device called ArmAssist, and a touch-screen computer with telerehabilitation and gaming software to train shoulder, elbow, wrist and finger movements and muscle force. Participants were instructed to train at least three hours per week for six weeks, but determined their own session time and duration.

A retrieving movement of a weight (0.5 kg) across a table was investigated. The participant started with the hand around the weight and the elbow extended (0°), he was instructed to bring it in a straight line towards the body. The retrieving task was performed with the least affected (LA) side and most affected (MA) side. Participants were measured before the start of the intervention (pre-test) and directly after the six-weeks training intervention (post-test). Four different conditions were each measured once: MA side pre-test (PreMA), LA side pre-test (PreLA), MA side post-test (PostMA) and LA side post-test (PostLA).

Kinematic data were acquired at 60 Hz using eleven inertial measurement units (IMUs) (Xsens MVN Awinda v2019, Xsens Technologies, Enschede, Netherlands). Sensor placement and calibration were performed according to the manufacturer's protocol [12]. The reported accuracy of the IMUs is 0.2–0.5° [12].

2.2. Data processing

The coupling angle was computed between shoulder abduction and elbow flexion since these are the major components of the pathological flexion synergy in stroke [9]. Elbow and shoulder angles were calculated in MVN Analyze using ZXY and XZY Euler sequences, respectively [12]. Custom-made MATLAB (Mathworks, Inc., v2018a, Natick (MA), USA) scripts were used to process and analyse the data. Data were filtered using a low-pass Butterworth filter with a 7 Hz cut-off frequency.

The elbow flexion angle was defined as 0° with the elbow fully extended, shoulder abduction angle was defined as 0° when the upper arm was vertical and parallel to the trunk. Two researchers (SGR and KAH) independently selected the start and end of the movement visually based on the elbow flexion angle and reached consensus.

2.3. Outcome variables

Kinematics: Angle-angle plots

Angle-angle plots of the elbow flexion angle vs. the shoulder abduction angle were created. Extracted kinematic outcomes were the range of motion (RoM) and duration of the movement.

Interjoint coordination: Coupling angle

The coupling angle was defined as the angle between the positive x-axis of a cartesian system and the vector between two adjacent time points, in an angle-angle plot (Fig. 1). Similar to Chang et al. (2008), equation 1 and 2 were used to calculate the coupling angle gamma (γ), where θ_E is the elbow flexion angle, θ_S is the shoulder abduction angle, and i represents every movement point in the normalized range 0-100% [13].

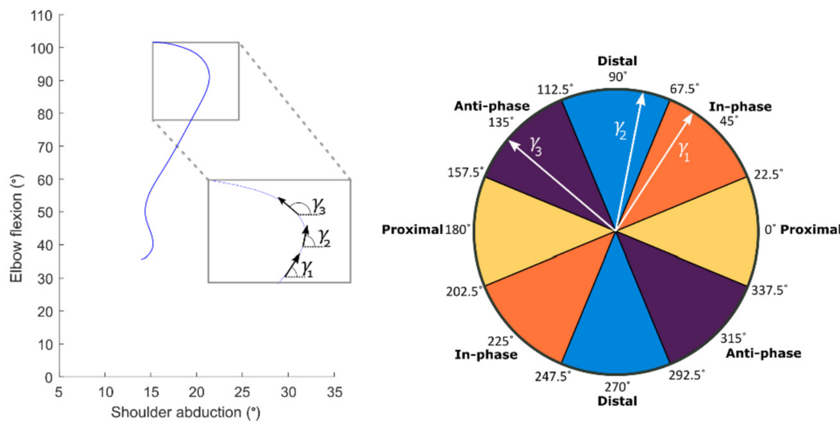

Fig. 1. Example illustrating an angle-angle plot (left) between shoulder abduction angle (x-axis) and elbow flexion angle (y-axis). The inset shows the calculation of the coupling angle (γ) at subsequent points in the movement ($\gamma 1$, $\gamma 2$, $\gamma 3$). The coloured circle (right) shows the categorization of the phases of the coupling angle using a mapping procedure where the phases are colour coded. ° = degrees.

$$\gamma_i = \tan^{-1}\left(\frac{\theta_{E,i+1} - \theta_{E,i}}{\theta_{S,i+1} - \theta_{S,i}}\right) * \frac{180}{\pi} \quad \text{if } \theta_{S,i+1} - \theta_{S,i} > 0 \tag{1}$$

$$\gamma_i = \tan^{-1}\left(\frac{\theta_{E,i+1} - \theta_{E,i}}{\theta_{S,i+1} - \theta_{S,i}}\right) * \frac{180}{\pi} + 180 \quad \text{if } \theta_{S,i+1} - \theta_{S,i} < 0 \tag{2}$$

Four phases of the coupling angle (range: 0–360°) were identified (Fig. 1): proximal and distal leading phase, in-phase and anti-phase. Mapping the different phases with colour codes helped reveal phase transitions and therefore movement's smoothness [14]. Furthermore, phase duration was calculated to determine how long the participant moved within each of the four phases. Statistical analysis was performed using SPSS (IBM SPSS for Windows, version 23, IBM Corp., Armonk, NY, USA). Due to the small sample size, descriptive statistics and nonparametric Wilcoxon signed rank tests were used. Comparisons were made between pre-post testing within sides (PreMA-PostMA and PreLA-PostLA), and between sides (PreMA-PreLA, PostMA-PostLA and deltaMA-deltaLA, where delta is the change between pre-posttest results). Effect sizes (r) were calculated using $Z/\sqrt{M}$, where Z is the Z-statistic and M is the number of observations. Effect sizes were classified as small (<0.3), medium (>0.3–<0.5) or large (>0.5) [15]. A significance level of $p < .05$ was used for all comparisons. Due to the small sample size, medium effect sizes were also discussed.

3. Results

3.1. Participants

Kinematic data of seven out of twelve participants was successfully acquired (participant characteristics: Appendix A, Table A.1). Data of two participants was not compatible due to an older version of Xsens being used. Two other participants could not be measured due to COVID-related house-visit restrictions, one participant withdrew from the study after three weeks because of illness and device discomfort.

3.2. Kinematics: angle-angle plots

Fig. 2 shows angle-angle plots of the participants. The elbow RoM was significantly smaller at PreMA compared to PreLA. The shoulder RoM was significantly smaller at PostMA compared to PostLA (Table 1, individual data: Appendix B, Table B.1).

3.3. Interjoint coordination: coupling angle

The angle-angle plots provide an initial insight into how movement execution differs between persons and how it changes before and after the training. The coupling angle, showed by colour mapping, highlights these differences (Fig. 3). The colour mapping allows to visually determine the quantity of the phases, the number of phase transitions and a coordination pattern.

A general coordination pattern could be distinguished in the LA side. The movement started with abduction of the shoulder and minimal elbow flexion, followed by an in-phase section, where both shoulder abduction and elbow flexion occurred. During the majority of the movement, the elbow joint was dominant, as shown by a distal leading movement. The movement ending was diverse, with either an anti-phase or a proximal leading phase.

The MA side showed more variability in the coordination pattern. The start of the movement consisted mostly of a proximal leading phase. The majority of the participants performed most of the movement in the distal leading phase, however there were multiple phase changes towards anti-phase or in-phase (Table 1, individual data: Appendix B, Table B.2).

4. Discussion

The coupling angle and the phase mapping provided a straightforward measure to visualize and quantify interjoint coordination, in this proof-of-concept study. The phase mapping is a feasible method to extract the interjoint coordination between the shoulder and elbow joint.

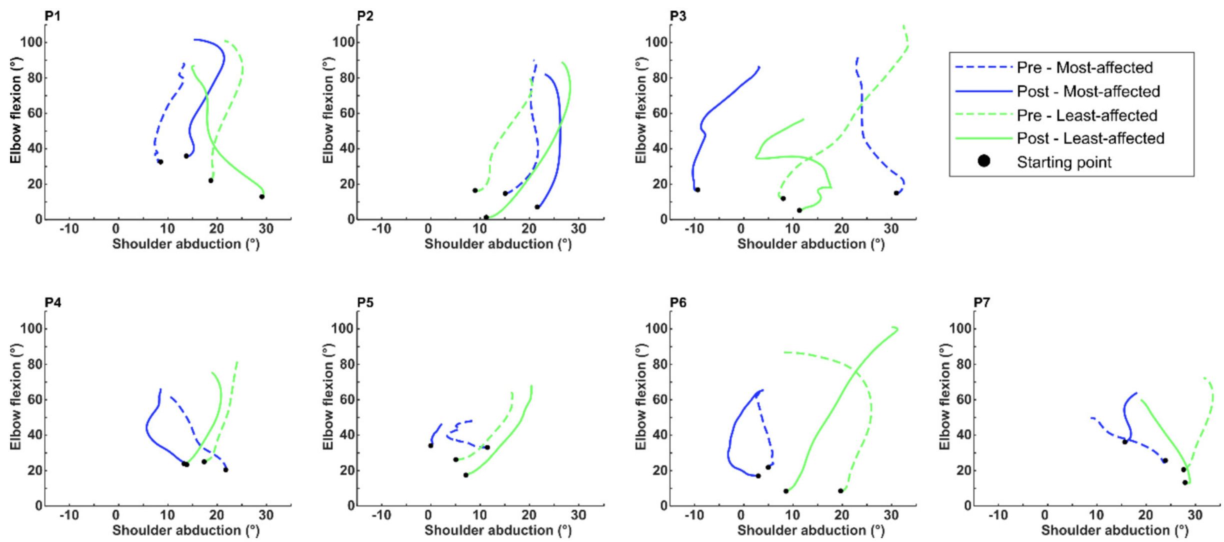

Fig. 2. Angle-angle plots of the elbow flexion angle and the shoulder abduction angle for the most affected (blue lines) and least affected (green lines) sides for the pre-test (dashed lines) and post-test (solid lines). The black dot is the starting point of the movement. The direction of the line indicates the direction of the coupling angle as can be seen in Fig. 1 and thus the leading joint and movement phase. A change in direction can indicate a phase transition. ° = degrees.

Table 1
Kinematics (upper part of the table) and interjoint coordination (lower part of the table) of the retrieving movement for the most affected side and least affected side, before and after the training. Displayed are the median values [interquartile range] (left half of the table) and P-values [effect sizes] (right half of the table).

	Median [IQR]				P-values [effect sizes]				
					Pre-test versus Post-test		MA versus LA		
	PreMA	PostMA	PreLA	PostLA	PreMA-PostMA	PreLA-PostLA	PreMA-PreLA	PostMA-PostLA	Delta MA-LA
ROM elbow	44.2° [25.2;75.3]	48.3° [27.7;70.0]	64.9° [51.6;78.5]	51.8° [51.6;87.9]	0.61 [0.14]	0.87 [0.05]	**0.03 [0.59]***	0.09 [0.45]#	1.00 [0.00]
ROM shoulder	8.2° [6.0;11.5]	7.2° [2.6;7.8]	11.4° [6.5;18.6]	14.6° [10.0;17.0]	0.50 [0.18]	0.24 [0.32]#	0.40 [0.23]	**0.03 [0.59]***	0.18 [0.36]#
Movement duration	1.27 s [0.9;3.2]	0.98 s [0.9;2.2]	1.25 s [0.8;1.7]	0.93 s [0.7;2.2]	0.18 [0.36]#	0.93 [0.02]	0.24 [0.32]#	0.46 [0.20]	0.24 [0.32]#
Distal	70% [39;82]	69% [63;82]	77% [67;79]	73% [68;83]	0.67 [0.11]	0.87 [0.05]	0.18 [0.36]#	0.67 [0.11]	0.35 [0.25]
In-phase	5% [2;20]	11% [6;18]	14% [7;22]	11% [8;20]	0.80 [0.07]	0.75 [0.08]	0.24 [0.32]#	0.29 [0.28]	0.93 [0.02]
Proximal	6% [1;8]	5% [1;10]	5% [1;8]	6% [5;8]	1.00 [0.00]	0.87 [0.05]	0.55 [0.16]	0.91 [0.03]	0.50 [0.18]
Anti-phase	16% [2;50]	6% [3;21]	5% [3;9]	5% [3;8]	0.50 [0.18]	0.80 [0.07]	0.13 [0.41]#	0.35 [0.25]	0.31 [0.27]
Phase transitions	6 [4;13]	6 [3;7]	4 [3;5]	5 [3;6]	0.19 [0.35]#	0.29 [0.28]	0.06 [0.51]*	0.68 [0.11]	0.06 [0.51]*

IQR = interquartile range, PreMA = pre-test most affected, PostMA = post-test most affected, PreLA = pre-test least affected, PostLA = post-test least affected, MA = most affected, LA = least affected. RoM = range of motion, % = percentage of the movement. Significant values are bold ($p < .05$). Effect sizes were large (dark green shade, *) or medium (light green shade, #).

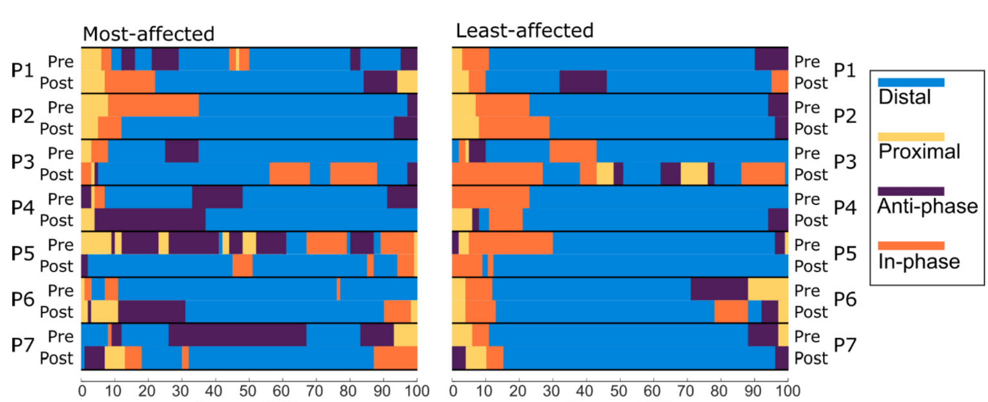

Fig. 3. Phases of the coupling angle with colour mapping showing the interjoint coordination between shoulder abduction and elbow flexion during a retrieving movement for all seven participants before (pre) and after (post) the intervention for both upper limbs. P = participant; % = percentage of the movement.

Significantly smaller elbow flexion angles in the MA side were found, as expected from previous literature [2,8,16]. However, the smaller abduction angles in the MA side compared to the LA side revealed that participants did not seem to use excessive abduction, as would be expected based on the pathological synergy, possibly because they were mildly to moderately affected. The task was completed with reduced shoulder abduction and elbow RoM, indicating that additional DoFs were used, particularly trunk flexion, as confirmed by the recorded videos.

Training seemed to have some effect on the coordination pattern. The shoulder seemed to be more involved during pre-test, as was seen in the longer anti-phase duration and larger number of phase transitions, showing increased segmentation of the movement on the MA side. After training, less phase transitions indicated less involvement of the shoulder joint involvement, which could facilitate a smoother movement execution. This might be the result of an improved ability to perform isolated joint movements using the elbow.

Some limitations need to be addressed. The number of participants was restricted by a limited availability of training devices and a narrow time measurement window. However, for determining the feasibility of the method, the number of participants seems appropriate. More repeated measurements and a larger population should be included to ascertain the training effects. Furthermore, this study's chronic stroke patients were moderately to mildly affected, while larger differences may be shown in a subacute population of stroke survivors.

In conclusion, the coupling angle combined with the colour mapping provided a straightforward tool to visualize and interpret the overall movement pattern. Although the training with an assistive rehabilitation device did not result in statistical differences in interjoint coordination, the methods used seem promising to investigate post-stroke interjoint coordination patterns.

Human and animal rights

The authors declare that the work described has been carried out in accordance with the Declaration of Helsinki of the World Medical Association revised in 2013 for experiments involving humans as well as in accordance with the EU Directive 2010/63/EU for animal experiments.

Informed consent and patient details

The authors declare that this report does not contain any personal information that could lead to the identification of the patient(s).

The authors declare that they obtained a written informed consent from the patients and/or volunteers included in the article. The authors also confirm that the personal details of the patients and/or volunteers have been removed.

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Author contributions

All authors attest that they meet the current International Committee of Medical Journal Editors (ICMJE) criteria for Authorship.

S.G. Rozevink: conceptualization, methodology, formal analysis, project administration, visualization, writing original draft, review & editing; K.A. Horstink: conceptualization, software, investigation, data curation, formal analysis, review & editing; C.K. van der Sluis: supervision, review & editing; J.M. Hijmans: supervision, review & editing; A. Murgia: conceptualization, methodology, formal analysis supervision, review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial or personal relationships that could be viewed as influencing the work reported in this paper.

Data availability

The dataset supporting the conclusions of this article is available via Dataverse NL: https://doi.org/10.34894/MBABRA.

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Appendix A. Table A.1

Table A.1
Overview of the participant characteristics.

Participant	Gender (M/F)	Age	Time after stroke (m)	Stroke type	Dominant side	Affected side	FMA-UE pre	FMA-UE post	WMFT pre	WMFT post	Training time (hrs)
P1	M	55	35	I	R	L	45	49	54	50	12.6
P2	F	66	19	I	R	L	51	49	66	71	21.9
P3	M	72	13	I	R	L	45	58	61	69	32.8
P4	M	68	32	I	R	R	37	52	49	54	18.6
P5	M	52	35	H	R	L	24	24	27	38	10.1
P6	M	73	35	I	R	R	27	33	39	40	19.5
P7	M	59	11	I	R	L	30	35	37	40	5.5
median [IQR]	6M/1F	66 [57;70]	32 [16;35]	6I/1H	7R/0L	2R/5L	37 [28.5;45]	49 [34;50.5]	49 [38;57.5]	50 [40;61.5]	18.6 [11.4;20.7]

P = participant; SD = standard deviation; M = male; F = female; m = months; I = ischemic; H = haemorrhagic; R = right; L = left; FMA-UE = Fugl-Meyer Assessment – upper extremity; WMFT = Wolf Motor Function Test; hrs = hours, IQR = interquartile range.

Appendix B. Tables B.1 and B.2

Table B.1
Kinematic outcomes (range of motion of the shoulder and elbow and movement duration) for each participant before (pre) and after (post) the intervention for the most-affected (MA) and least- affected (LA) sides.

Participant	Side	ROM elbow (°)		ROM abduction (°)		Time (s)	
		Pre	Post	Pre	Post	Pre	Post
P1	MA	55.8	65.8	6.0	7.5	2.13	0.98
	LA	78.5	73.4	6.5	14.6	0.77	0.82
P2	MA	75.3	74.8	6.7	4.4	0.63	0.57
	LA	64.9	87.9	11.4	17.0	0.65	0.60
P3	MA	78.7	70	9.7	13.5	1.27	2.23
	LA	101.1	51.8	26.2	15.4	1.42	2.55
P4	MA	41.4	42.1	11.5	7.8	1.08	0.95
	LA	58.6	51.7	6.6	7.2	0.77	0.67
P5	MA	14.9	11.6	8.2	2.1	3.23	3.08
	LA	37.6	51.6	11.4	13.3	1.67	3.27
P6	MA	44.2	48.3	3.4	7.2	3.78	1.97
	LA	78.1	92.5	18.6	22.7	1.25	1.23
P7	MA	25.2	27.7	15.2	2.6	0.83	0.85
	LA	51.6	47.0	5.8	10.0	1.77	0.93
Total MA (median [IQR])		44.2 [25.2;75.3]	48.3 [27.7;70.0]	8.2 [6.0;11.5]	7.2 [2.6;7.8]	1.27 [0.83;3.23]	0.98 [0.85;2.23]
Total LA (median [IQR])		64.9 [51.6;78.5]	51.8 [51.6;87.9]	11.4 [6.5;18.6]	14.6 [10.0;17.0]	1.25 [0.77;1.67]	0.93 [0.67;2.23]

P = participant, RoM = range of motion, MA = most-affected, LA = least-affected, IQR = interquartile range, ° = degrees, s = seconds.

Table B.2
Interjoint coordination outcomes (number of phase transitions and phase duration for all four phases) for each participant before (pre) and after (post) the intervention for the most-affected (MA) and least-affected (LA) sides.

Participant	Side	Phase transitions (n)		Phase duration (%)							
				Distal		In-phase		Proximal		Anti-phase	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
P1	MA	13	4	70	63	5	14	8	12	16	10
	LA	3	5	80	73	7	8	3	5	9	13
P2	MA	3	3	63	82	26	6	8	5	2	6
	LA	3	3	72	68	15	20	7	8	5	3
P3	MA	4	8	82	69	4	26	3	1	9	3
	LA	6	13	79	33	14	42	8	1	5	8
P4	MA	6	2	71	63	2	0	1	3	25	33
	LA	1	5	77	78	22	9	0	5	0	7
P5	MA	17	7	12	86	20	11	16	1	50	1

Table B.2 (*continued*)

Participant	Side	Phase transitions (n)		Phase duration (%)							
				Distal		In-phase		Proximal		Anti-phase	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
	LA	5	3	67	88	24	11	5	0	3	0
P6	MA	6	6	90	60	8	7	1	10	0	21
	LA	4	6	60	71	7	17	15	6	17	5
P7	MA	7	7	39	69	2	18	6	6	52	6
	LA	4	4	78	83	4	4	8	6	9	4
Total MA (median [IQR])		6 [4;13]	6 [3;7]	70 [39;82]	69 [63;82]	5 [2;20]	11 [6;18]	6 [1;8]	5 [1;10]	16 [2;50]	6 [3;21]
Total LA (median [IQR])		4 [3;5]	5 [3;6]	77 [67;79]	73 [68;83]	14 [7;22]	11 [8;20]	5 [1;8]	6 [5;8]	5 [3;9]	5 [3;8]

P = participant, MA = most-affected, LA = least-affected, IQR = interquartile range, n = number, % = percentage.

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