Cadernos Brasileiros de
Terapia
Ocupacional
Brazilian Journal of Occupational Therapy

ISSN 2526-8910

Original Article

The effects of kinesthetic and visual motor imagery on interjoint coordination in the hemiplegic index finger: an experimental study using the index of temporal coordination

Os efeitos da imagem cinestésica e viso-motora na coordenação interfalângica do dedo indicador hemiplégico: um estudo experimental usando o "the index of temporal coordination"

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How to cite: O'Brien J., Bracewell, R. M. & Castillo, J. A. (2021). The effects of kinesthetic and visual motor imagery on interjoint coordination in the hemiplegic index finger: an experimental study using the index of temporal coordination. *Cadernos Brasileiros de Terapia Ocupacional, 29*, e2170. https://doi.org/10.1590/2526-8910.ctoAO2170

Abstract

Upper limb hemiparesis is a common impairment following stroke and can affect interjoint coordination. Motor imagery training is one treatment strategy. However, motor imagery can use visual or kinesthetic modalities and there has been a lack of research comparing the effectiveness of these modalities when treating the upper limb. The aim of this study was to compare visual and kinesthetic motor imagery in improving interjoint coordination in the hemiparetic index finger. Fifteen stroke survivors with upper limb hemiparesis were allocated to groups using kinesthetic or visual motor imagery, or a control group using guided relaxation. Reaching and grasping movements of the upper limb were captured using optoelectronic motion capture. Interjoint coordination of the hemiparetic index finger was analysed using the index of temporal coordination. No significant differences were found for interjoint coordination following treatment in either condition. Future work should focus on comparing kinesthetic and visual motor imagery in the rehabilitation of more proximal upper limb joints.

Keywords: Stroke, Motor Skills, Finger Joint.

Received on Oct. 9, 2020; 1st Revision on Nov. 19, 2020; Accepted on Dec. 12, 2020.

Resumo

A hemiparesia do membro superior é uma incapacidade comum após o AVC e pode afetar a coordenação das articulações interfalângicas. A terapia por imagens motoras é uma estratégia de tratamento. No entanto, essa terapia de imagem motora pode usar modalidades visuais ou cinestésicas e há uma escassez de pesquisas que comparem a eficácia dessas modalidades no tratamento do membro superior. O objetivo deste estudo foi comparar a terapia por imagem viso-motora e cinestésica na melhoria da coordenação interfalângica no dedo indicador hemiparético de pessoas com AVC. Quinze participantes com hemiparesia de membro superior foram alocados em grupos cuja terapia foi por imagens cinestésicas ou viso-motoras, e um grupo controle cuja terapia foi de relaxamento guiado. Movimentos de alcance e preensão com o membro superior foram capturados por meio de captura de movimento optoeletrônica. A coordenação interfalângica do dedo indicador hemiparético foi analisada por meio do instrumento “temporal coordination index”. Nenhuma diferença significativa foi encontrada para a coordenação interfalângica após o tratamento em qualquer condição. O trabalho futuro deve se concentrar na comparação das imagens cinestésicas e viso-motoras na reabilitação das articulações mais proximais dos membros superiores.

Palavras-chave: Acidente Vascular Cerebral, Destreza Motora, Articulações dos Dedos.

Introduction

Stroke is a leading cause of disability throughout the world and a key impairment is upper limb hemiparesis, a loss of strength and dexterity affecting one side of the body (Machado et al., 2016). Motor imagery, involving mental rehearsal of a movement without executing it, has been proposed as a treatment strategy (Barclay-Goddard et al., 2011). One systematic literature review has found that, with regard to the treatment of upper limb hemiparesis, motor imagery is most effective when preceded by physical practice (Schuster et al., 2011). However, a randomised controlled trial, involving 121 stroke survivors with upper limb hemiparesis, evaluated motor imagery when used alongside what the authors describe as “standard” rehabilitation and failed to identify any significantly different results between the experimental and control groups (Ietswaart et al., 2011, p. 1378). Ietswaart et al. (2011) study may have been limited by using the Action Research Armtest (ARA) as the key outcome measure. ARA was developed for the clinical setting (Lyle, 1981) and is scored by an individual assessor. A systematic review has identified scope for ‘measurement error’ with ARA and opposing evidence regarding its ability to reliably detect small changes in performance (Pike et al., 2018, p. 459). We suggest, therefore, that ARA may not be effective when seeking to capture fine-grained changes in joint rotation following motor imagery treatment. We contend that fresh approaches to researching the use of motor imagery in upper limb hemiparesis that address these limitations may be warranted.

We identified two areas meriting further investigation. First, motor imagery can use a kinesthetic modality (KMI), where the person imagines the feeling of a movement, or a visual modality (VMI), which involves imagining the appearance of a movement (Dickstein & Deutsch, 2007). Brain imaging indicates that VMI and KMI are linked to activity in distinct areas: VMI correlates with activation in visual cortical areas, while KMI correlates with activity in motor regions including the putamen, caudate and cerebellum (Guillot et al., 2009). Researchers have also noted different motor behavioral effects of VMI and KMI. Grangeon et al. (2011), for example, measured the variability of postural sway, defined as the variability of centre of pressure in relation to base of support, as participants stood on a force platform performing KMI and VMI of jumping. Variability was significantly higher during KMI and the authors argue that this could be explained by findings that KMI preferentially activates neural motor regions, which may lead to greater postural sway, when compared with VMI (Grangeon et al., 2011). This may support the preferential use of KMI in an intervention aimed at motor rehabilitation, which was our concern in this study. With reference to stroke, Kim et al. (2011) tested people with post-stroke lower limb hemiparesis under four separate conditions: KMI, VMI, KMI with an auditory cue, and VMI with an auditory cue. The researchers found significantly faster performance on the Timed Up and Go Test, along with significantly higher electromyogram activity for the gastrocnemius, for KMI with an auditory cue when compared with VMI alone (Kim et al., 2011). Notwithstanding these findings, Nilsen et al. (2010) note that the studies included in their systematic review of motor imagery in post-stroke upper limb hemiparesis probably combined VMI and KMI in a single treatment but did not make this explicit. These authors also argue that insufficient work has been done to comparatively evaluate VMI and KMI in the rehabilitation of the hemiparetic upper limb (Nilsen et al., 2010). Our research therefore addressed this.

The second area we identified concerned the dependent variables used to evaluate motor imagery. The coordination of joint movements in order to achieve a movement goal is regarded as a key aspect of efficient motor control (Bernstein, 1967) and one feature of upper limb hemiparesis is impaired interjoint coordination, characterized by altered timing of joint rotations (Lum et al., 2009). Outcome measures that focus exclusively on the final motor goal of grasping an object, for example, without regard to the underlying ‘elemental motor patterns’, may fail to distinguish goal achievement via compensatory movement of the trunk towards the object from accomplishment underpinned by improved interjoint coordination; they might, therefore, tell us little about the effectiveness of a particular treatment in enhancing the quality of upper limb motor control (Levin et al., 2009, p. 315). These insights regarding joint intercoordination jibe with the views of Braun et al. (2013), who note that the effects of motor imagery may be at the level of movement coordination and precision, suggesting that fine-grained measurements may be needed to capture changes in these variables. In keeping with this, we analysed changes in the timing of interjoint coordination following VMI and KMI using optoelectronic motion capture as recommended by Hewett et al. (2007), who maintain that this technique facilitates reliable measurement of detailed movement characteristics. We measured interjoint coordination by calculating the “index of temporal coordination” (TCI), initially described by Cirstea et al. (2003, p. 290). TCI permits analysis of the coordination of the timing of joint movements. In our case, we analyzed TCI for three joints of the hemiparetic index finger during the ‘approach’ and ‘hold’ segments of an upper limb movement towards an object. Our dependent variable was the size of the difference between the phase angles for the joints in each segment. Our prediction was that improved interjoint coordination would be characterized by a reduced difference between the phase angles of the joints. Using this approach, we were able to assess the impact of KMI and VMI on components of motor performance known to be impaired in upper limb hemiparesis. To the best of our knowledge this had not been done previously.

The purpose of our study, then, was to evaluate the effects of VMI and KMI on interjoint coordination in upper limb hemiparesis. As shown above, evidence suggests that KMI may preferentially facilitate activity in neural motor regions and consequently in muscles, when compared with VMI and Mulder (2007) has argued, on this basis, that KMI may be a more effective strategy for motor rehabilitation. We therefore predicted, with respect to our dependent variables, that KMI would be associated with greater changes in the timing of index finger joint interaction in the hemiparetic hand when compared with VMI.

Method

Participants

Fifteen patients (6 male, 15 right-handed, 10 with right-side hemiparesis, 5 with left-side hemiparesis, mean (SD) age 60.4 (13.02) years) with a diagnosis of stroke were recruited. Fourteen were recruited from hospitals in Bogotá, D.C., Colombia. Another patient was recruited via a university contact. All spoke Spanish as a first language. Inclusion criteria were:

(a) over 18 years of age;

(b) hemiparesis affecting the hand;

(c) scoring above one on the hand activities component of the Motor Assessment Scale (MAS), indicating that, as a minimum, the person was able to lift an object while maintaining wrist extension. The MAS has been shown to demonstrate both reliability and validity (Carr & Shepherd, 1998);

(d) scoring above 20 on the Mini-Mental State Examination (MMSE); scores below 20 have been found to be a valid cut-off which indicate the presence of dementia and the MMSE has also demonstrated reliability (Folstein et al., 1975)[1];

(e) scoring four or less on the Modified Ashworth Scale, indicating that, at the greatest level of impairment, the clinician would have difficulty passively stretching the hemiparetic upper limb (Wade, 2000). This assessment has been shown to demonstrate inter-rater reliability when used to test upper limb muscle tone (Bohannon & Smith, 1987);

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[1] Participant 11 scored 13 on the MMSE. She was dysphasic. However, she was orientated to time, place and person, showed no evidence of apraxia and could follow spoken commands, for example she was able to follow the instructions to perform the tasks required for the MAS. It was felt therefore, in line with the World Medical Association declaration of Helsinki, that she could give informed consent and that her MMSE score resulted from expressive communication difficulties. The informed consent form was read to her prior to signing and she indicated that she understood its content. All screening, treatment and testing was carried out in the presence of her adult daughter, who was her main carer.

(f) able to walk and transfer independently (these criteria controlled for person factors that could increase the risk of slips and trips);

(g) normal or corrected to normal vision in order to control for low vision as an extraneous variable.

None of the participants were receiving other occupational or physiotherapy treatment.

In addition, participants were tested using the Kinesthetic and Visual Imagery Questionnaire (KVIQ), devised by Malouin et al. (2004). KVIQ uses self-rated clearness of visual imagery and intensity of imagined kinesthetic experience as criteria for motor imagery performance, with a higher score indicating greater ability. We did not include this as an inclusion criterion, however we were interested to know if there were any statistically significant differences for motor imagery ability between the treatment groups prior to testing. KVIQ was translated into Spanish by one of the authors.

All individuals who met the criteria agreed to take part. Participant characteristics are shown in Table 1; screening test scores are shown in Table 2.

Table 1. Participant characteristics.

Participant	Age	Gender	Time since stroke	Dominant hand	Affected side
1	48	F	2 months	R	L
2	64	F	3 weeks	R	R
3	79	M	20 days	R	L
4	64	M	3.5 years	R	R
5	45	F	3 weeks	R	R
6	55	F	11 days	R	R
7	55	F	3 weeks	R	R
8	64	M	1 month	R	R
9	51	M	2 months 3 weeks	R	R
10	74	F	3 weeks	R	L
11	73	F	2 weeks	R	R
12	43	M	3 months	R	R
13	74	F	2 months	R	L
14	76	M	4 months	R	R
15	41	F	8 days	R	L

Ethics

Ethical approval was given by the ethical review committee of the University of Rosario in line with the principles of the Declaration of Helsinki. All participants gave informed voluntary consent by reading and signing an information sheet approved by the committee.

Design

A between-within design was used. The 'between' factor consisted of independent groups treated with KMI, VMI, or a control treatment of guided relaxation. The 'within' factor consisted of repeated measures of interjoint coordination for all groups, pre- and post- treatment.

Materials and Procedure

We specified a target grasp posture for the hemiparetic hand. This was the 'lumbrical grip', involving flexion of the metacarpophalangeal (MCP) joints with simultaneous extension of the interphalangeal joints, facilitated by the hand lumbrical muscles. These muscles originate on the tendons of flexor digitorum profundus and insert into the dorsal digital expansion, an arrangement that facilitates control over the coordination of proximal interphalangeal (PIP) and distal interphalangeal (DIP) joints. This allows the muscles to provide proprioceptive feedback from those joints; and means that they play an important role in fast, dextrous movements (Leijnse & Kalker, 1995; Palastanga et al., 2006; Schreuders & Stam, 1996). The lumbrical grip was chosen for three reasons. First, we believe fine motor function assists in performance of activities of daily living, making the lumbrical muscles an appropriate focus for treatment. Second, specifying the lumbrical grip meant that we had, implicitly, made a pattern of interjoint coordination in the hemiparetic fingers a goal for our participants. Third, this approach aligned with Rosenbaum et al. (2001), who argue that reaching and grasping involves advance selection of a final hand posture.

We felt that the lumbrical grip would be challenging to perform and all participants, therefore, received two sessions involving ten repetitions of a physical treatment protocol, aimed at strengthening the hemiparetic lumbrical muscles and providing a kinesthetic prompt regarding their action, via light resistance exercises. Treatment was delivered by one of the authors, a senior occupational therapist specialized in the treatment of adult upper limb hemiparesis and was in line with the approach developed by the British Bobath Tutors Association, as outlined by Champion & Lynch-Ellerington (2009).

When the physical treatment sessions had been completed, motion capture was commenced. Reflective markers were attached using clear, double-sided adhesive tape to the index finger tip, and the DIP, PIP and MCP index finger joints and thumb MCP of the hemiparetic hand. Markers were also placed on the thumb tip and distal aspects of the ulna and radius, although these were not used for subsequent analysis. The position of the markers is shown in Figure 1.

Joint angles were defined as follows: MCP was the vertex of virtual lines between the markers on the thumb MCP and the index MCP and the markers on the index MCP and the PIP; PIP was the vertex of virtual lines from the markers on the index MCP and the PIP and the markers on the PIP and the DIP; and DIP was the vertex of virtual lines from the markers on the PIP and the DIP the markers on the DIP and the index tip.

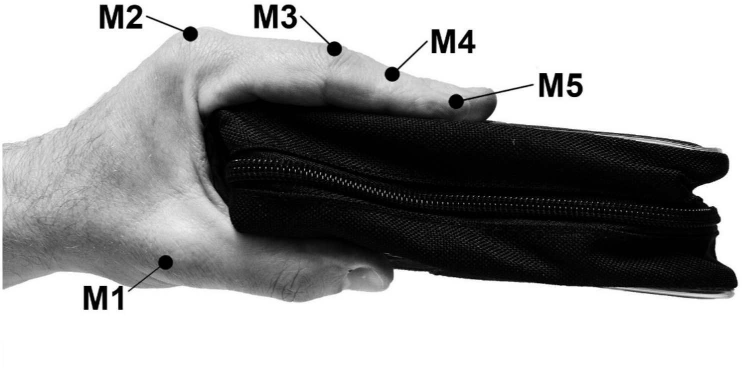

Figure 1. Location of joint markers used for kinematic analysis. M1: thumb metacarpophalangeal joint; M2: index finger metacarpophalangeal joint; M3: index finger proximal interphalangeal joint; M4: index finger distal interphalangeal joint; M5: index finger tip.

The participants sat comfortably at a desk and watched a video displaying a hand grasping a black compact disc (CD) case using the lumbrical grip. The video had a recorded commentary describing the lumbrical grip and explaining that grasping the case using this grip was the task to be executed during motion capture. While this task could potentially be executed with either dominant or non-dominant hands, we specified that the participants should use their hemiparetic limb.

There were four videos, showing a female and male right and left hand performing the grip, each repeated five times. Women with left-sided hemiparesis viewed the video of the female left hand, men with right-sided hemiparesis watched the video of the male right hand, and so on. The video and commentary were presented on a laptop computer.

We used a video and recorded commentary for two reasons. First, this standardized the initial presentation of the task, thus reducing the risk of bias. Second, evidence suggests that observation of an action via video can facilitate motor learning of that action (Hayes et al., 2010).

The participant subsequently placed the hemiparetic hand in a comfortable starting position on the desk. He or she then grasped a CD case, aiming at using the lumbrical grip to do this, with their hemiparetic hand. The CD case was 15.5 cm deep, 16.5cm high and 5cm wide. It was filled with CDs and weighed 600g. It was placed on its side, with the spine facing the participant in the sagittal plane. Once they had grasped the case, they released it and returned the hand to the starting position. The trunk and less affected upper limb were not restrained, although only the hemiparetic upper limb was used in the reach.

In order to capture precise data and analyze the kinematics of the hemiparetic index finger, optolectronic motion capture was used. This constructs a coordinate system from X, Y and Z axes, allowing capture of the joint's movement in three dimensions. Movement was captured at 50Hz using the BTS Smart six-camera system. Fourteen reach and grasps were performed and captured optoelectronically.

Following the initial movement capture of fourteen reach and grasps the participants were treated using motor imagery or guided relaxation: these were one-off sessions that consisted of six repetitions of a motor imagery script and five repetitions of the relaxation script. They then performed reach and grasp movements once more, which were also captured optoelectronically. They were allocated to one of three groups. These were: a group using KMI (*n*=5); a group using VMI (*n*=5); and a control group using guided relaxation (*n*=5).

Eleven participants, including all those in the KMI and VMI groups, were randomly allocated to group using Random Allocation Software (Saghaei, 2004). Four were not randomized, in order to allow for equal numbers in each group.

The KMI script lasted for 7 min 20 s, the VMI script for 8 min 12 s and the relaxation script for 7 min 24 s. These are provided in Appendix 1. All the interventions involved spoken instructions in Spanish from a native speaker of Colombian Spanish, delivered via a tape recording through headphones.

Once they had listened to the appropriate script for their group, the participants were required to reach for the CD case again, once more aiming to grasp with the lumbrical grip. Fourteen reach and grasp movements were again captured optoelectronically.

There was variation in the intervals between capture of baseline kinematic data, treatment and capture of post-intervention kinematics. However, this was never more than a few minutes and depended upon the needs of each participant.

Data Reduction and Analysis

Movement onset and offset

Data were exported as text files and stored on spreadsheets. Data reduction was accomplished using Matlab R2007a (Mathworks Inc, 2007).

Movement onset and offset points for each reach and grasp were identified by looking at the velocity curve for the PIP joint. Since the arm was transporting the hand towards the object, and the hand was simultaneously preparing to grasp, the rotational movement of the finger joint occurred together with translational movement of the joint towards the CD case. We therefore took PIP movement as an appropriate proxy measurement of upper limb movement. Specifically, we identified two velocity values at or below ± 10 degrees per second (deg/s); this was because these values were taken as points where the joint was nearly still, prior to and following reaching and grasping. If the curve between these two points had two distinct peaks enclosing a middle segment where the velocity fell to below 20% of the peak velocity of the curve for more than 10% of the reach and grasp movement time, then the curve was taken to represent the movement of the joint during one reach and grasp. The middle segment was taken as the hold segment, in which the hand was relatively stable as it grasped the CD case. One such movement cycle, based on interpolated data, is shown in Figure 2.

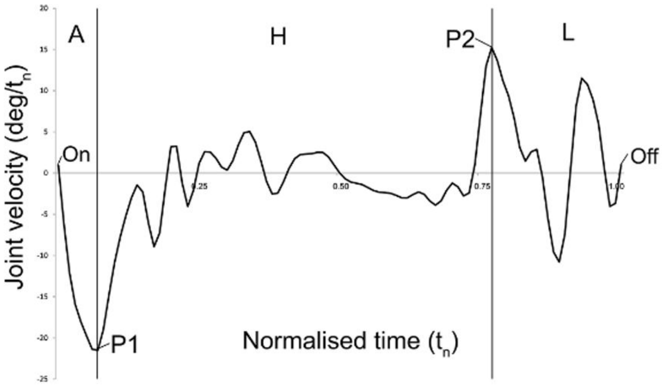

Figure 2. Plot of velocity (deg/t_n) profile for the PIP joint during one reach and grasp movement for participant six, prior to KMI treatment. On: movement onset; off: movement offset; P1: first peak; P2: second peak; A: approach segment; H: hold segment; L: leave segment; t_n: unit of normalized time.

Five grasps were selected from the 14. Where possible, these movements were selected from the middle of the sequence to control for initial practice time and fatigue. However, artefactual issues meant that occasionally not all of the five central movements were adequately captured and movements were selected from nearer the start or end of the sequence.

The timing for each reach and grasp was normalized. The data for each joint of interest were interpolated using splines, involving the identification of third order polynomials and allowing the estimation of the curve connecting two consecutive data points. Advantages of splining include: provision of a curve which approximates closely to the original data; suitability for data captured at relatively low sampling rates, as ours were; and effectiveness when interpolating noisy data, which we expected would characterize that captured from hemiparetic finger joints (Robertson & Caldwell, 2004).

Time normalization and interpolation allowed the data for the five movements selected for each participant to be presented on a spreadsheet in an array consisting of five columns and 101 rows, representing 0-100% of the movement. The data were then combined by calculating a mean value for each row, providing a single column of data with 101 rows that constituted an ensemble average for the whole movement. This process was carried out for each joint, giving ensemble averages for MCP, PIP and DIP joint paths for all participants. The ensemble averaged data for each joint for each participant were then smoothed by filtering using a dual low-pass second order Butterworth filter with a cut-off rate of 6Hz.

We used plots of the ensemble-averaged data for MCP, PIP and DIP joint position through time to identify landmarks dividing different movement segments. First, we identified an initial steep change in the curve as the hand grasped the CD case and another as the hand released it. Second, we verified these points against the ensemble-averaged velocity curve for that joint. If the data points on the velocity curve which corresponded to the two points we had identified on the position curve were at or near zero, suggesting that the joints were nearly still at those points, we assumed that the segment between the two steep position curve changes represented the period in which the hand was still and grasping the case.

Three distinct segments of the movement were identified: the approach, as the participant reached for the CD case; the hold, as the hand actually grasped the case; and the leave, as the hand released the case. This is illustrated in Figure 3.

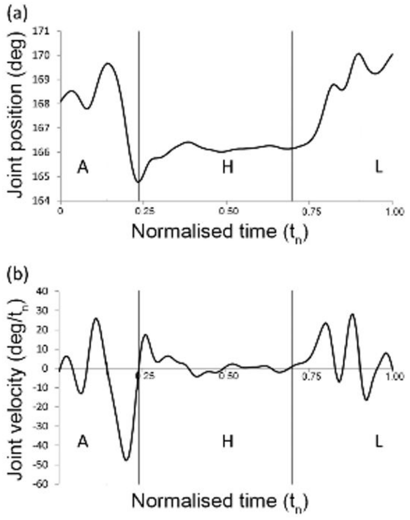

Figure 3. (a) Participant 7 pre-VMI PIP joint path and (b) pre-VMI PIP velocity showing location of reaching and grasping segments. A: approach segment; H: hold segment; L: leave segment. t_n: unit of normalized time.

Interjoint coordination

TCI is calculated by first combining the changing magnitude of a joint angle over time with the changing angular velocity of that joint to produce a single variable and then measuring the difference of this variable between two joints (Cirstea et al., 2003).

The steps we took to calculate TCI are as follows. First, we plotted angle-angular velocity diagrams showing joint angle position and joint angular velocity throughout the movement for MCP, PIP and DIP for each participant before and after treatment. We then calculated phase angles (ϕ) by finding the arctangent of the x and y coordinates of each data point of the angle-angular velocity diagram. The phase angle is the angle formed by a line along the x axis to the origin of the graph and a line running from the origin to a data point on the curve representing the x,y coordinates, that is, joint position and joint velocity, respectively.

By subtracting the phase angle values for one joint from another, for example ϕ_{MCP} - ϕ_{PIP}, we were able to calculate the TCI for these joints. Thus we had TCI values for ϕ_{MCP} -ϕ_{PIP}, ϕ_{MCP} - ϕ_{DIP} and ϕ_{PIP} - ϕ_{DIP} for all groups before and after treatment. Graphs showing the procedure used to calculate TCI are contained in Figure 4.

We then calculated the amplitude of the TCI curves. We did this by taking the root mean square (RMS) of the TCI values for each segment of the movement. We predicted that improved coordination would be distinguished by a smaller RMS, as this would indicate that there was less difference between the phase angles for each joint.

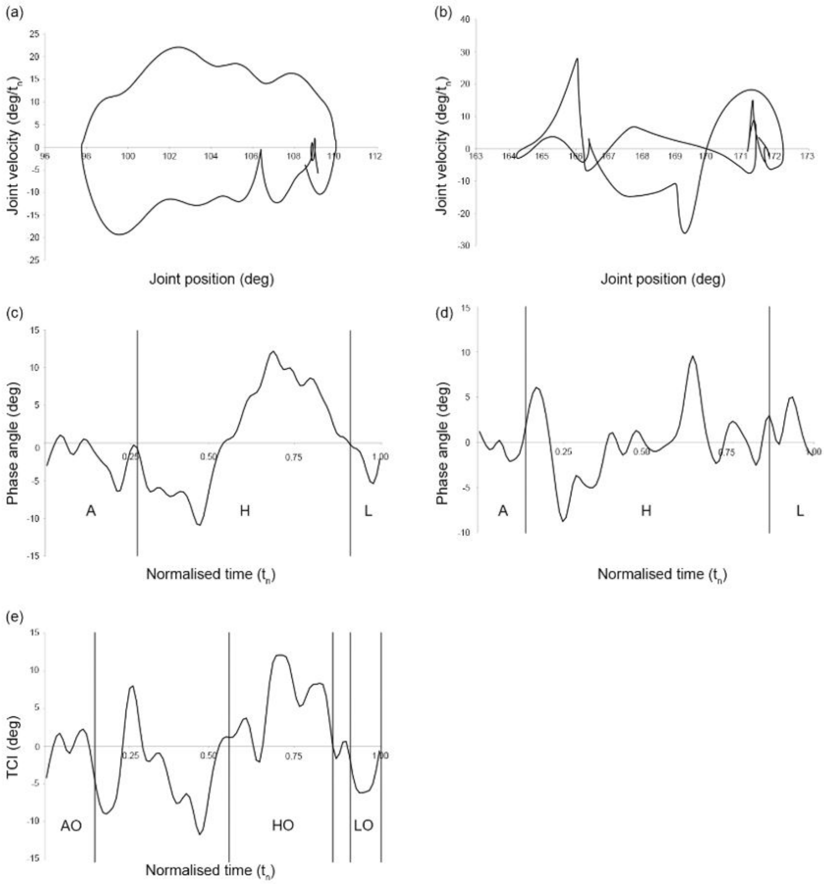

Figure 4. (a) Angle-angular velocity diagram for MCP joint of participant two following KMI treatment; (b) Angle-angular velocity diagram for PIP joint of participant two following KMI treatment; (c) Phase angle of MCP joint of participant two following KMI treatment; (d) Phase angle of PIP joint of participant two following KMI treatment; (e) TCI for MCP and PIP joints of participant two following KMI treatment showing areas of overlap in approach, hold and leave segments. AO: approach overlap; HO: hold overlap; LO: leave overlap; TCI: temporal coordination index; t_n: unit of normalized time.

Statistical Analysis

The data captured from the tests used to screen for inclusion in the study were derived from parametric scales and testing with Levene's test revealed homogeneity of variance. The test results were therefore compared for significant differences using a one-way analysis of variance (ANOVA).

Dependent variable measures were compared using a 3 x 2 (Treatment [KMI, VMI, relaxation] x Time [pre-treatment, post-treatment]) between-within factorial analysis of variance (ANOVA). The repeated measures within-factor was 'time' and the between-factor was 'treatment'. The cut-off for statistical significance for all ANOVAs was $p = < .05$.

Statistical tests were carried out using SPSS Version 24 (IBM Corp., 2016).

Results

Screening tests

There were no significant differences between the treatment groups for the upper limb component of the MAS, *F*(2,12) = 0.75, *p* = .493. Neither were there any significant differences for the hand component of the MAS, *F*(2, 12) = 0.23, *p* = 0.798, nor for the advanced hand component of the MAS, *F*(2,12) = 0.214, *p* = .81. Furthermore, there were no significant differences between the scores for the visual component of the KVIQ, *F*(2, 12) = 0.271, *p* = .767, nor for the kinesthetic component, *F*(2, 12) = 0.259, *p* = .776. The screening test scores are shown in Table 2.

Table 2. Screening test scores.

Test			
	MAS (Upper limb)		
	Mean	**SD**	***p***
KMI	5.6	0.55	0.493
VMI	5.4	0.55	
Relaxation	5.8	0.45	
	MAS (Hand)		
KMI	4.4	1.94	0.798
VMI	4.6	1.51	
Relaxation	5	0	
	MAS (Advanced hand)		
KMI	1.6	0.55	0.810
VMI	1.8	1.09	
Relaxation	1.4	1.14	
	Ashworth		
KMI	3.4	0.89	0.546
VMI	3.2	0.45	
Relaxation	2.8	1.1	
	MMSE		
KMI	27.8	2.95	0.263
VMI	27.2	2.39	
Relaxation	23.4	6.54	
	KVIQ (visual component)		
KMI	57.4	10.31	0.767
VMI	50	27.25	
Relaxation	49	17.76	
	KVIQ (kinesthetic component)		
KMI	53.6	17.27	0.777
VMI	44.6	27.39	
Relaxation	50	11.87	

MAS: Motor Assessment Scale; MMSE; Mini Mental State Examination; KVIQ: Kinesthetic and Visual Imagery Questionnaire.

TCI segment amplitude

There was a main effect of time for the MCP-PIP hold segment, *F*(1,12) = 6.657, *p* =.022, however there was no interaction effect of treatment and time. There was a main effect of time for the PIP-DIP approach segment, *F*(1,12) = 7.269, *p* = .019, however there was no interaction effect of treatment and time. There was also a main effect of time for the PIP-DIP hold segment, *F*(1,12) = 7.231, *p* =.020, however there was no interaction effect of treatment and time. The TCI amplitude results are summarized in Table 3.

Table 3. Results for dependent variables

Dependent variables	Main effect of time		Main effect of treatment		Interaction effect of treatment and time	
	F	***p***	***F***	***p***	***F***	***p***
			TCI segment amplitude			
MCP-PIP approach	.317	.584	.872	.443	.493	.623
MCP-PIP hold	6.657	.022*	3.146	.08	.171	.845
MCP-DIP approach	4.727	.05	.373	.696	3.824	.052
MCP-DIP hold	3.473	.087	2.696	.108	1.166	.344
PIP-DIP approach	7.269	.019*	.597	.566	.501	.618
PIP-DIP hold	7.231	.020*	2.130	.162	.868	.445

**p* <.05

Discussion

The purpose of this study was to compare the effects of KMI and VMI on the timing of interjoint coordination in the index finger of the hemiparetic upper limb in stroke survivors. We did not identify any significant differences between the participants on screening test scores; they were therefore comparable in terms of motor imagery ability and motor function. We predicted that KMI would be linked to a change in the temporal characteristics of finger joint interaction during reaching with the hemiparetic upper limb. Specifically, we predicted that improved interjoint coordination would be characterized by a smaller difference between the phase angles of joints. Our results did not confirm this prediction.

In the following discussion we address two areas. First, we identify some technical difficulties and limitations in our study. Second, we ask if analysis of interjoint coordination using TCI may still be considered a useful method for evaluation of the effects of motor imagery in upper limb hemiparesis.

Some earlier research on the role of motor imagery in the motor rehabilitation of stroke survivors has failed to control aspects of the accompanying physical treatment (Jackson et al., 2001). This could be a source of bias and a benefit of our study was that we standardized the physical treatment given to each participant. There were two treatment sessions, with ten repetitions of lumbrical muscle strengthening in each. It may be the case, however, that this was not enough to achieve lasting strengthening of the muscles. Future work should therefore involve an increase in the intensity of strength training.

Our null results might also be explained by biomechanical factors. It is known that the absolute force generated by finger flexors is greater than that of finger extensors, and that this pattern persists in upper limb hemiparesis (Colebatch & Gandevia, 1989). In our study, the effort applied by the flexor digitorum profundus and flexor digitorum superficialis muscles at the distal and middle phalanges respectively, which represent comparatively light loads, may have been difficult for the weakened lumbricals to resist, leading to PIP and DIP being pulled into flexion (Tortora & Derrickson, 2011). So, while we maintain with Scholz (1990) that interjoint coordination patterns are an important component of motor control that can be impaired in hemiparesis, it may be appropriate in future to focus on more proximal joints, for example the shoulder and elbow. This would offer the advantage of working with larger muscle groups, avoiding the marked force imbalance between the extrinsic hand muscles and lumbricals, and also with greater loads, represented by the humerus, ulna and radius.

The structure of our intervention was similar to that of Yágüez et al. (1999), who captured movement kinematics from neurological patients while executing an upper limb task, followed by a single motor imagery session lasting ten minutes and then a repetition of the task and repeated motion capture; these authors noted improvements in movement kinematics following MI training. We used a guided relaxation task as a control condition, following Page et al. (2007). We believed this was appropriate as it engaged the participants' attention in a mental task for a similar time as the motor imagery conditions and was also presented via the same medium; at the same time, however, it was distinct from them in that it was not based on imagery and did not make reference to the lumbrical action. We deployed a one-off session of motor imagery with six repetitions of the imagery script and five of the relaxation script during the session. The frequency and number of repetitions was intended to ensure that similar times were allotted to each treatment condition. In addition, the frequency was in line with the suggestion of Schuster et al. (2011) that there should be no more than two repetitions of motor imagery per minute. Regarding the choice of a one-off session with multiple repetitions, our rationale was twofold. First, evidence shows that the average time spent on upper limb rehabilitation following stroke in acute settings may be as little as 7.9 minutes per day, suggesting that there is very little time for this therapy (Serrada et al., 2016). Second, researchers have identified that imagery based treatments are not being used in clinical practice and we felt that our approach could, for example, be delivered by therapy assistants, making clinical application more likely (Stockley et al., 2019). Overall, we were concerned to evaluate a rapid treatment that could be applied in an acute environment with a high throughput of patients. We were also aware of findings that a single motor imagery session may cause activation of cortical motor regions in stroke survivors (Sharma et al., 2009) and also findings of improved weight-bearing in the hemiparetic lower limbs of stroke patients during a sit-to-stand task following one-off motor imagery (Malouin et al., 2004). Regarding this latter research, we would suggest, once more, that it may be important to take biomechanics into account, in that the lower limb combines powerful muscle groups with large levers and also that motor control during sit-to-stand benefits from feedback from ground reaction force (Yamada & Demura, 2010). Neither of these advantages apply to the finger joints and we propose, therefore, that findings regarding the effects of motor imagery on lower limb recovery may not be directly relevant to work on the upper limb. Furthermore, we suggest that future work in this area on the upper limb post-stroke should entail more than a one-off session of motor imagery training.

In our study, participants were free to adopt the starting posture they felt most comfortable with. The trunk was not constrained and the hand starting position was not specified in advance. This was because the execution of the reaching and grasping task using a pre-specified grip posture was challenging enough, without further limitation on the degrees of freedom of body segments. Also, given that the participants had differing levels of impairment, it was not possible to instruct them to place their hands at the same starting point. Overall, therefore, there was no control for compensatory trunk movement or distance covered. However, since we were taking isolated measurements of the angular rotation of finger joints, this should not have affected our results regarding interjoint coordination. Nevertheless, the constraint of the degrees of freedom of other body parts may be considered in subsequent research.

Limitations also include the small sample size. This is explained by the practical difficulties of identifying appropriate participants and safety concerns meaning that participants had to be recruited and tested consecutively. It is perhaps useful to point out that other studies of mental imagery with stroke survivors have had comparable sample sizes: Page et al. (2001), for example, had thirteen, while Cicinelli et al. (2006) had seventeen. Also, no mean and standard deviation values from pilot data or similar research were available and therefore calculations of power and sample size were not undertaken. These procedures need to be done in future research on this topic and a larger sample size should be aimed at.

Another limitation was the failure to randomly allocate the final four patients. In studies with small sample sizes, imbalance in group numbers can itself be a source of bias, allowing confounding variables present at baseline to influence results (Kang et al., 2008). We therefore made a prior decision to have equal numbers in each group. At the same time, practical and safety considerations meant that participants were recruited and tested consecutively, meaning that our decision to equalize the group numbers made true randomization effectively impossible. It is felt that this trade-off between potential sources of bias did not threaten the internal validity of the research for two reasons: first, electronic motion capture and data processing reduced the threat of observer bias; second, the training materials and physical treatment protocol were delivered in a standardized manner. Nonetheless, random allocation to treatment group should be aimed at in future work.

Our study was not blinded. There were two practical reasons for this: first, the nature of the intervention meant that it was not possible to conceal from the participants the treatment condition they were assigned to; second, resource limitations meant that one researcher was both administering treatment and capturing the data. Barclay-Goddard et al. (2011) have highlighted the difficulty of ensuring blinding in research on motor imagery in stroke and Ietswaart et al. (2011), for example, report that blinding was achieved in only 86% of the stroke survivors in their study, and report that many authors fail to report whether studies were blinded or not. In mitigation, we believe that our use of electronic measurement techniques helped to reduce the threat of bias and we aim to support blinding in future work.

A further issue concerns the appropriate time since stroke and level of recovery at which to measure interjoint coordination. As this was a convenience sample, we did not control for chronicity, and time since stroke ranged from 8 days-3.5 years, although no significant motor ability differences were identified within our sample. Other studies of interjoint coordination following stroke have been more diverse: in Levin's (1996) study of intercoordination of the elbow and shoulder, for example, the range was from 0.5-7.2 years post-stroke and scores on the Fugl-Meyer scale of motor skill ranged from 19-66. Overall, however, we do not believe that the measurement of interjoint coordination in the post-stroke hemiparetic hand has been undertaken before and are not aware of any normative data on the optimal time or level of motor function for data capture. We suggest that this should be explored in future work.

Studies of motor imagery in upper limb hemiparesis are marked by similar heterogeneity regarding chronicity and level of recovery. In Page et al. (2007) study, for example, which identified significant differences in post-treatment measures that favoured the use of the technique, the mean time since stroke was 3.6 years, with a range of 12-174 months, although no significant differences in motor skill at baseline were detected. While it has been suggested that brain recovery occurring spontaneously may plateau at six months post-stroke (Nudo, 1999), these results indicate that motor imagery treatment may be effective sometime after this. The precise mechanisms underpinning neural plasticity and recovery of function are subject to continuing research and debate (Ekusheva & Damulin, 2015; Nudo, 2007) and we suggest that the development of guidelines on the best time to implement motor imagery will need to take place in tandem with this.

Three possible sources of bias that we did not control for were handedness, type of stroke, and side of stroke. In relation to handedness, all of the individuals in our sample were right handed but only five had left sided hemiparesis: this could be a limitation, as it has been found that recovery from upper limb hemiparesis may be better if the lesion site is in the dominant hemisphere (McCombe Waller & Whitehall, 2005). Regarding type of stroke, three were hemorrhagic, nine were either ischemic or not classified, and for three a radiology report was unavailable. The influence of stroke type remains an open question: one group of researchers has identified that survivors of hemorrhagic strokes may make greater improvement following rehabilitation (Kelly et al., 2003), another has noted that those with lacunar infarcts had a recovery advantage (Ween et al., 1996), while others have not found any difference in the post-rehabilitation recovery levels of those with hemorrhage or ischemia (Perna & Temple, 2015; Przysada et al., 2017). In relation to handedness, researchers have noted that motor imagery deployed by stroke survivors with left hemisphere lesions may facilitate increased activity in the contralateral motor cortex; while motor imagery used by those with right hemisphere stroke does not facilitate activity in either motor region (Stinear et al., 2007). Overall, we suggest that stroke type, handedness, and side of stroke are variables that should be explored in subsequent work.

The importance of cognitive screening in this area is underlined by work suggesting that motor imagery depends upon the mechanisms of working memory (Sharma et al., 2006) and research showing significant positive correlation between working memory ability and motor recovery when using imagery following stroke (Malouin et al., 2004). We used the MMSE, which assesses areas including language, calculation and drawing (Cockrell & Folstein, 2002). It may be the case, however, that more in-depth cognitive screening of thinking and perceptual skills is warranted, and this should be undertaken in future.

Conclusion

In this study we predicted that KMI would be associated with changes in the timing of interjoint coordination in the hemiparetic finger, as measured by TCI. Our results did not confirm these predictions.

Despite our null results we suggest that TCI has potential in that it captures high resolution changes in motor control and, if used alongside a functional outcome measure, has a clinical application. Regarding the assessment of motor imagery's impact on motor control in the hemiparetic upper limb, we argue that future research might usefully focus on the interaction of more proximal joints alongside increased dosage of motor imagery and greater intensity of strength training.

Acknowledgements

Jonathon O'Brien was supported by the Wales Office of Research and Development. We would like to thank Dr. Stephen McKinnell for his assistance with graphics.

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Author's Contributions

Jonathon O'Brien contributed to the design of the study, data analysis and writing the article. Robert Martyn Bracewell contributed to the design of the study and writing the article. Juan Alberto Castillo contributed to the design of the study.

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Editor de seção

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Appendix 1

Guided breathing script preceding KMI, VMI and relaxation (repeated six times for KMI and VMI and three times for relaxation)

‘Focus on your breathing, breathe in and out normally, forget about any other sounds in the room or outside the room, just focus on your breathing. Put any worrying thoughts out of your mind. Close your eyes if you wish, but don’t let yourself fall asleep’.

Script used for KMI treatment (repeated six times)

‘Now relax your muscles. Relax the side of your body which has been affected by the stroke. Relax the hand which has been affected by the stroke. Now remember the video of the hand grip which you saw earlier. I want you to imagine your weak hand making that movement. Keep your hand quite still. Imagine the feeling of the knuckles bending and the fingers straightening at the same time, the knuckles bending upwards and the fingers staying quite straight. Keep your hand very still, just imagine the feeling of the movement’.

Script used for VMI treatment (repeated six times)

‘Picture your weak hand. Imagine you are looking at it, but keep your hand quite still. Now imagine you can see your fingers moving, but do not really move your hand, keep it quite still. Imagine you can see your knuckles beginning to bend, but at the same time imagine you see your fingers staying quite straight. Imagine you can see your hand in the position you have practised in therapy and watched on the video, which is with your knuckles bent, but your fingers straight out. Careful not to really move your hand, just imagine you can see it moving’.

Script for relaxation treatment (repeated five times)

‘Focus on the sensation in your legs and feet and then let your legs and feet relax. Next focus on the sensation in your hands and arms, and let your hands and arms relax. Now you are quite relaxed, focus on the sounds in the room around you. Now concentrate on your breathing for a while longer, just breathe normally’.

Reorientation script (read after KMI, VMI and relaxation)

‘Now become aware of the room again, if you have had your eyes closed open them and look around you. The session has now ended’.