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Coordination between reaching and grasping in patients with hemiparesis and normal subjects

Abstract

Objectives: To investigate the coordination of reach-to-grasp components in hemiparetic and normal subjects.

Design: Split plot repeated measures design with three factors (group, object size, movement speed)

Setting: Movement laboratory

Participants: Twelve hemiparetic and twelve age matched normal subjects

Methods: Motion analysis was used to collect information on the kinematic variables of movement duration, peak velocity, peak deceleration, maximum aperture, and the time of peak velocity, peak decleration and maximum aperture expressed as a percentage of movement duration during 32 reaching movements for each subject. Coordination between the two components was examined in two ways. First, the correlation between time of hand opening and start of hand transport, and between time of maximum aperture and time of peak deceleration was investigated. Second, movements at preferred and fast speeds (manipulation of transport component) and to two different sized cups (manipulation of grasp component), were compared.

Results: Both groups demonstrated a temporal coupling between grasp and transport components at the start of the reach and at the time of maximum aperture. Both groups increased the aperture of grasp for larger cups and increased the maximum grip aperture and had a shorter deceleration phase for faster movements. However, the deceleration phase of the hemiparetic patients was longer than normal subjects and the components were not as tightly coupled.

Conclusions: This group of patients with a moderate amount of functional recovery did show similarities to normal subjects in their ability to control reach-to-grasp components. However, their performance was not as skilled.

Key words: stroke; rehabilitation; arm; physical therapy; hemiparesis

Introduction

Reach-to-grasp of objects is a key feature of normal upper limb function. The kinematic analysis of these movements reveals at least two components. For a given movement the hand follows a characteristic path and trajectory as it moves towards an object, described as the ‘transport’ component (change over time of the position of the wrist marker [1])~~[1]~~ and the hand opens and closes on the object, the ‘grasp’ component (change over time of the distance between the index finger and thumb markers [1])~~[1]~~. Neurophysiological evidence supports separate but interdependent visuomotor control channels for these two components [2 3 4 5]. Transport and grasp must be coordinated to ensure that the object is grasped successfully. There is evidence that an invariant temporal relationship exists between the two components, where the start time of the opening of the hand is correlated with the start time of hand movement towards the object [6 7], and the time of maximum hand opening is correlated with the time of peak deceleration of the hand [6 8 9]. The latter relationship is stronger for larger objects [10]~~[10]~~, although it is not a consistent finding in all subjects. The exact temporal relationship depends on the goal of the task, object properties and the experience of the performer [10].

Further evidence of temporal interdependence is seen when one component adjusts in response to manipulations of the other component. For example, a faster transport results in an increased maximum grip aperture size [11 12]. When grasping objects of smaller sizes, a proportionally longer deceleration phase and an increase in movement duration occurs [8 10 13 14 15]. Moreover, performing an additional opening and closing of the grasp during the transport phase, causes a longer movement duration with a high correlation between peak velocity of the wrist and the second maximum grip aperture -[16]~~[16]~~.

Analysis of the kinematics of reach-to-grasp in people with hemiparesis may permit identification of specific motor control deficits and enable these findings to serve as a basis for therapy. However, there have been only a small number of kinematic studies of reach-to-grasp movements in patients with hemiparesis. Those that exist are primarily restricted to features other than temporal coordination of grasp and transport components and many concentrate on movements of the less affected arm.

In the hand contralateral to the lesion, peak velocity is lower and more variable than controls, but occurs within the first 50% of the movement duration [17]~~[20]~~ [18]. One study by Michaelsen et al [19] has specifically reported on temporal coordination between grasp and transport and found this to be largely preserved, with percentage time of maximum aperture and maximum aperture size not significantly different from controls and maximum aperture occurring in the deceleration phase. Two other studies demonstrate that both transport and grasp show deficits in accuracy and that grasp shows deficits in efficiency (directness of movement to target) [20] [21].

Previous studies of the hand contralateral to the lesion have not specifically assessed the invariant temporal relationship between transport and grasp at the start of the reach and at the time of peak deceleration, nor have they assessed temporal interdependence when one component adjusts in response to manipulations of the other component. Therefore we aimed to investigate whether a group of patients with hemiparetic arm movements had (i) temporal coupling of transport and grasp at the time of start of movement and at the time of peak deceleration, and (ii) the ability to to adjust for manipulation of grasp on transport and vice versa, compared to age-matched controls. In contrast to Michaelsen et al [19] the present study analysed movements of the hemiparetic arm in an earlier stage of recovery in order to better inform rehabilitation strategies for these patients, and used a task closer to those performed in real life, since experimental constraints such as the selection of objects and the goal of the task may determine neural patterning [9]~~[9]~~. The study will provide a more detailed understanding of coordination of grasp and transport in patients with stroke than has been given previously.

Given that the basic parameters of reach-to-grasp can be similar to that of normal subjects, we hypothesised that the coordination between the two components would to some extent be preserved.

Materials and methods

Subjects

Twelve patients with a diagnosis of hemiparesis were recruited consecutively from one hospital and were selected according to functional ability and stroke classification. Diagnosis was confirmed by CT scan where possible (Table 1). The following inclusion criteria were used: 1) A score of between 5 and 12 on the arm section of the Rivermead Motor Assessment [22]. A score of 5 requires the patient to “reach forward, pick up a large ball with both hands and place down again”. 2) Able to reach and grasp a cup containing water and attempt to take a drink. 3) A middle cerebral artery infarct (classified as PACI or TACI on the Bamford classification for cerebral infarction [23]). These patients commonly have arm impairment and constitute a large number of the patients presenting for rehabilitation.

The group can be summarised as being 1-6 months after their stroke with sensory problems, spatial awareness problems and mild increased muscle tone. There were eight patients with non-dominant lesions and four with dominant lesions. Further details of patient characteristics are shown in Table 2. The use of the side ipsilateral to the hemisphere affected as a control was rejected, as both strength [24] and response to stretch [25] in the ipsilateral arm are different to that of normal subjects. Therefore, twelve normal control subjects were recruited and matched to the hemiparetic patients for age, sex, and whether their dominant or non-dominant hand was used in the experiment. All normal subjects were within normal range (i.e. normal mean + two standard deviations) on the Ten Hole Peg test [26~~35~~]. The normal subject group (8 women and 4 men) had a mean age of 64.8 years. The hemiparetic group (7 women and 5 men) had a mean age of 66.9 years. Informed consent was obtained from all subjects according to the declaration of Helsinki. Ethical approval was granted by the Nottingham City Hospital Ethics Committee.

(Table 2 near here)

Research Protocol

Subjects participated in four conditions. To test the effect of manipulation of the transport component on grasp, subjects reached at two different speeds – preferred and fast. To test the effect of manipulation of the grasp component on transport, subjects reached for two different sizes of cup. Subjects were seated on a height-adjustable chair at a table with their waist touching the table edge in front. Movement was recorded in three dimensions using a MacReflex motion analysis system [27]. The calibrated workspace measured 90 cm long by 60 cm wide and 125 cm high. Two cameras with charge coupled device, infrared flash and automatic gain control were positioned above the subject, one in front and one above the shoulder. These recorded the movement of reflective markers attached to the wrist (radial styloid process), the lateral surface of the index finger (between the distal interphalangeal joint of the finger and the finger nail) and the medial surface of the thumb (between the distal interphalangeal joint of the thumb and the thumb nail). The markers were sampled at 50 Hz. The mean static and dynamic constant spatial error for this experimental set-up were calculated [31] as 0.58mm and 0.88mm respectively. Variable error for the dynamic test was 0.21mm.

Reaches were made to a cup of two different dimensions placed at a constant distance, at two different speeds. Subjects grasped either a large cup half-filled with water (height 11 cm, top diameter 7cm , weight 0.17 kg) or a small cup, also half-filled with water (height 7 cm, top diameter 6 cm, weight 0.07 kg), which was placed 20 cm anterior to the starting position of the hand. Both cups tapered to a slightly narrower base (large 5.2 cm diameter, small 4.7 cm diameter). Although the weights of the two cups were different, object weight has been shown to affect only the length of time for which the hand is in contact with the cup, and does not affect the transport component [32]~~[38]~~. So that markers could be clearly seen by the cameras, subjects were instructed to grasp the upper portion of the cups.

Data acquisition and analysis

The starting position specified that the finger and thumb tips were lightly touching, the forearm was in mid-pronation, the elbow was at approximately 100 degrees flexion and the wrist rested on a marker (20 cm posterior to the cup) indicating the start position. The other arm rested in the subject's lap. In all conditions, subjects were instructed to "Reach forward, pick up the cup and have a sip of water, then place the cup back on the table. Use your whole hand to grasp the cup, if possible". In conditions 3 and 4 an additional instruction was given, "Reach as fast as you can without knocking over the cup or spilling the water". The computer emitted a tone as a signal for the subject to move. Subjects naturally used a whole hand grasp for both sizes of cup, though some subjects did not contact the small cup with all four fingers.

A practise session occurred prior to the beginning of data collection, in which subjects practised grasping both small and larger cups, between three and five times, at their preferred speed. There was a five minute rest between practice and the start of data collection. Each condition constituted 8 trials, with 32 in total. Conditions 1 and 2 were reaches to large and small cups respectively, at the subject's preferred speed. Conditions 3 and 4 were reaches to the large and small cups respectively, at faster speeds. Trials at preferred reach-to-grasp speeds were performed first followed by the two faster speed conditions, in order to preserve two distinct reach-to-grasp speeds. To reduce fatigue and practice effects, trials in conditions 1 and 2 were randomised, with separate randomisation of conditions 3 and 4. So that fatigue did not prevent hemiparetic patients performing fast movements, a further 5 minute rest occurred after conditions 1 and 2 had been completed. Each of the 12 hemiparetic patients performed a different random order of trials, with the random order for each normal subject matched to that of the relevant hemiparetic subject.

For each recorded movement, the positions of the markers were identified manually in an editing process for three consecutive frames, after which the markers were automatically tracked through their trajectories using MacReflex software. Automatic tracking was observed on screen and manual tracking was occasionally used when the software indicated that a marker position did not equate with the approximate position predicted by the programme tracking the marker. Two-dimensional marker positions were then converted into three-dimensional coordinates using MacReflex software. In cases where markers were invisible to the cameras, a cubic spline algorithm was applied to predict the missing values. Data were filtered using a Bartlett filter with thirty-nine coefficients and with a cut-off frequency of 10 Hz.

The trajectory, velocity, and acceleration of the wrist marker were used to describe the transport component of the reach. Movement onset was determined as the time at which the three-dimensional velocity exceeded 25 mm.sec $^{-1}$ using a Gaussian weighted average (average velocity value was calculated by adding the velocity value at one frame to the values at the two frames before and after the frame and dividing the total by five). The end of transport was defined as the first time at which the maximum distance of the wrist marker, in the combined x, y (horizontal) plane was achieved. The z plane was not included as the task included bringing the cup to the mouth after grasp. Other determinants for the end of transport which have been used in investigations of normal reach-to-grasp, such as the time at which the distance between the thumb and finger markers becomes constant [9] or the time at which the velocity reaches a chosen low velocity or zero value [10] were found to be inappropriate for the functional abilities of the patients with hemiparesis. The patients were occasionally unsuccessful at grasping the cup, and it is common for hemiparetic patients to reach a low or zero velocity during the reach, as their trajectory can occur in a stepwise fashion [17]. Movement duration refers to the time between onset and end of transport. The time to wrist peak velocity and wrist peak deceleration were determined and expressed in absolute and proportional (i.e. as a percentage of movement duration) terms.

The trajectory of the thumb and finger markers described the grasp component. The start of hand opening was determined as the time at which the planar (three-dimensional) distance between the thumb and finger marker exceeded 0.58 mm (static spatial error), using a Gaussian weighted average (using 5 values as for movement onset). Maximum grip aperture was determined as the maximum planar distance between the thumb and finger marker. The time to maximum grip aperture was determined and expressed in absolute and proportional terms.

To answer the first research question concerning whether a temporal relationship exists between transport and grasp, Pearson's Product Moment Correlation coefficients were used to assess whether the start of hand opening was correlated with the start of hand transport, and whether the absolute time of peak deceleration was correlated with the absolute time of maximum grip aperture. Within group correlation coefficients were calculated separately for each condition. Thus 8 coefficients (2 groups x 4 conditions) were calculated to examine the correlation at the start of the movement. Similarly, 8 coefficients were calculated to test the correlation at the time of maximum grip aperture. To test significance of r values and whether correlations differed between the stroke and control groups, r values were transformed to z values and the significance of the difference between z values tested according to Fisher [33].

To answer the second research question, concerning interdependence between transport and grasp, a direct comparison between patients and age-matched controls was performed using a split-plot repeated measures ANOVA with one between-subject factor (group: stroke, control) and two within-subject factors (speed, cup size). The kinematic variables inserted into this analysis were movement duration, peak velocity, maximum aperture and time of peak velocity, peak deceleration and maximum grip aperture, all expressed as a percentage of movement duration. Variability of the movements, indicated by the coefficient of variation (standard deviation divided by the mean of a set of 8 trials) of maximum grip aperture, percentage time to peak velocity, percentage time of peak deceleration and percentage time of maximum grip aperture were compared using the same analysis. Significance levels of $p<0.05$ were used for all statistical comparisons.

In addition, specific tests were performed on the hemiparetic group data to assess the effect of neglect, spatial perception, pain and increased muscle tone on coordination of reach-to-grasp. For each clinical variable, patients were divided into 2 groups according to whether the patients demonstrated the particular clinical deficit.Then, spilt plot with repeated measures ANOVAs were performed on the kinematic variables with the between subject factor as presence or absence of the clinical deficit (neglect, spatial perception, pain and spasticity).

Results

Relationship between grasp and transport at the start of the reach

In the normal group, start time of aperture and start time of transport were significantly correlated in all conditions (large, preferred r = .80; small, preferred r = .83; large, fast r = .88; small, fast r = .91, all $p<0.05$). In the stroke group, start time of aperture and start time of transport were also significantly correlated in all conditions (large, preferred r = .31; small, preferred r = .78; large, fast r = .69; small, fast r = .86, all $p<0.05$). In the large cup conditions, the two events were significantly more highly correlated in normal subjects than in stroke subjects for both fast and preferred speeds ($p<0.05$). There was no difference in the correlations between groups in the small cup conditions.

Relationship between grasp and transport at the time of maximum grip aperture

In the normal group, time of maximum aperture and time of peak deceleration were significantly correlated in all conditions (large, preferred r = .30; small, preferred r = .57; large, fast r = .35; small, fast r = .68, all $p<0.05$). In the stroke group, time of maximum aperture and time of peak deceleration were also significantly correlated in all conditions (large, preferred r = .33; small, preferred r = .56; large, fast r = .71; small, fast r = .49, all $p<0.05$). In the fast conditions, the two events were more highly correlated in stroke subjects for the fast, large condition and in control subjects for the small, fast condition. There was no difference in correlations between groups in the slow conditions.

Comparison of groups, and speed and size conditions

Stroke subjects were slower than normal subjects ($F_{1,22}$=29.94, p<0.01). As expected, movement duration was shorter for fast movements ($F_{1,22}$=94.58, p<0.01). There were significant interactions for group x speed ($F_{1,22}$=14.52, p<0.01) and group x size ($F_{1,22}$=5.73, p<0.01), with larger differences in movement duration for stroke subjects compared to normal subjects between preferred and fast conditions, and between large and small cups (movement duration was longer for the large cup).

Peak velocity was higher in normal subjects ($F_{1,22}$=56.98, p<0.01) and higher for fast movements ($F_{1,22}$=172.25, p<0.01), corresponding to the results for movement duration. There was a significant interaction for group x speed ($F_{1,22}$=9.23, p<0.01) with larger differences for normal subjects compared to stroke subjects in peak velocity between preferred and fast conditions.

Peak velocity and peak deceleration occurred earlier in the movement for stroke subjects than normal subjects (percentage time of peak velocity, %TPV: ($F_{1,22}$=25.13, p<0.01); percentage time of peak deceleration, %TPD ($F_{1,22}$=23.82, p<0.01)). Faster movements had a later %TPV and %TPD ($F_{1,22}$=32.82, p<0.01 and $F_{1,22}$=23.08, p<0.01 respectively). There were significant interactions for group x speed for %TPV ($F_{1,22}$=4.35, p<0.01) and %TPD ($F_{1,22}$=6.18, p<0.01), with larger differences for normal subjects compared to stroke subjects between preferred and fast conditions.

There was no significant difference in maximum aperture size between the groups. As expected, the maximum aperture was larger for the large cup ($F_{1,22}$=66.46, p<0.01). Maximum aperture was larger for faster movements ($F_{1,22}$=12.99, p<0.01). Time of maximum aperture (%TMA) was later for faster movements ($F_{1,22}$=5.12, p<0.01). There was a significant group x speed interaction ($F_{1,22}$=11.41, p<0.01), with larger differences for normal subjects compared to stroke subjects in %TMA between preferred and fast conditions. There was a significant speed x size interaction ($F_{1,22}$=4.16, p<0.01), with larger differences in %TMA for the large compared to the small cup in between preferred and fast conditions. There was also a significant group x speed x size interaction ($F_{1,22}$=5.79, p<0.01), where for the small cup, %TMA was earlier for stroke subjects in the comparison between preferred and fast conditions, whereas it was later for normal subjects.

Means and standard deviations of all kinematic parameters are shown in Table 3.

(Table 3 near here)

Regarding variability, (described by coefficients of variation) stroke subjects were significantly more variable than normal subjects for %TPV ($F_{1,22}$=25.33, p<0.01), %TPD ($F_{1,22}$=44.16, p<0.01), %TMA ($F_{1,22}$=16.46, p<0.01) and maximum aperture ($F_{1,22}$=31.68, p<0.01). For faster movements, variability of %PVT was significantly greater for faster movements compared to those at preferred speed ($F_{1,22}$=8.32, p<0.01), but there were no other effects of condition.

Additional tests assessing effects of clinical parameters

In the analysis of the effect of neglect, pain, spasticity and spatial loss, there were no significant differences between groups in any of the kinematic variables, and only one significant interaction. This was a group x speed in movement duration between patients with or without spatial loss ($F_{1,22}=5.16$, $p<0.01$), showing that subjects with spatial loss move faster in the fast condition than those without spatial loss.

Discussion

Relationship between reach-to-grasp components

The hemiparetic patients demonstrated a temporal coupling between grasp and transport resembling normal subjects, since there was a significant correlation between start of aperture and start of transport, and between time of maximum aperture and time of peak deceleration, in all control and stroke subjects. From the results it would appear that compared to controls, correlations are lower at the start of the movement for stroke subjects when grasping the larger cup (at both speeds). Also, at the time of maximum aperture, their correlations were lower than controls when grasping the small cup at a fast speed. So although they behave similarly, the events are not so tightly coupled in stroke subjects as they are in controls.

Interdependence between the two components

Effects of speed

In response to faster movements, both normal subjects and hemiparetic patients increased the maximum grip aperture. While temporal variability can decrease with faster movements [34] spatial variability can increase as there is less time to make corrections based on visual feedback. [11]. Patients with hemiparesis opened slightly wider in fast movements than normal subjects, which could be a compensation for their increased spatial variability over and above that which occurs in healthy subjects. It is clinically significant that the hemiparetic patients demonstrated the increase in maximum grip aperture because it is a common clinical observation that they have difficulty in opening the hand [35] (Davies, 1985 p. 40) and Colebatch and Gandevia [24] reported that the extensors of the fingers and thumb were weaker than the corresponding flexors. This aspect of the relationship between grasp and transport has therefore been relatively unaffected, or has recovered well, in this group of patients.

The timing of transport events in faster movements was different from normal subjects. In the hemiparetic group, peak velocity, peak deceleration and maximum aperture occurred earlier. Therefore, the hemiparetic group spent relatively more time in the phase after peak deceleration compared to controls. Since this is the period where feedback is more likely to be used to adjust the movement, it may be that hemiparetic patients need to use this feedback control phase more than normals in order to compensate for increased movement variability and thus improve accuracy. This result is in contrast to the results of Farne et al [36] for the ipsilateral arm, where the deceleration phase was shorter than for normal subjects, indicating that the motor control problems of contralateral and ipsilateral arms are not identical.

Both groups demonstrated a later %TPV and %TPD, and thus a shorter deceleration phase, in the faster movements. This response to the faster condition was less marked in the stroke subjects compared to the normal subjects. It is likely that the later %TPV and %TPD reflects the fact that a greater part of the movement is centrally programmed (ballistic) and a smaller amount is used for adjustment, to meet the demand of the increased speed. If this is so, it would seem that the stroke subjects show more reliance on the feedback control phase as speed increases, than normal subjects. Both groups also showed a later %TMA in the faster movements. This response to the faster condition was also less marked in the stroke subjects compared to the normal subjects. The later %TMA implies that the grasp phase of the movement was delayed to maintain coordination with the delayed %TPV and %TPD in the transport phase.

Effect of cup size

It is usual for the maximum grip aperture to increase in size in accordance with the size of the object [14]. The ability of the hemiparetic group to adjust the aperture to object size with these two objects 1 cm different in their diameter, indicates an ability to make subtle adjustments in grip aperture. Further work is needed to see if this ability is present with a larger difference in object diameter.

The difference in movement duration between cup sizes reached significance in the hemiparetic group but not in the normal group. The smaller cup would be expected to produce a longer movement duration in the normal group, as in previous studies [8 14]. However, the normal subjects did not show a difference in movement duration for cup size. This may be attributable to the fact that the cups differed more in height than width, since Bootsma and van Wieringen [15] have demonstrated that width is a more influential factor in determining the length of the deceleration phase. Another reason could be that the difference in cup width was relatively small compared to size differences in previous studies [8 14]. Interestingly, the stroke subjects did show a difference in movement duration for cup size, but in the opposite direction to that expected of normals, i.e. the duration was longer for the larger cup. We hypothesise that the larger cup is more difficult to grasp for stroke subjects, because of their weak finger extensors [24], and therefore more time is needed to accomplish the larger grasp. Regarding the timing of %TMA, the large cup induced a more marked delay in %TMA with faster movements, and this was more marked again with normal subjects compared to stroke subjects.

In terms of the clinical significance of the statistically significant results,the differences across conditions for stroke subjects were generally smaller than that for normal subjects (%TPV, %TPD and %TMA, Table 7). This may indicate that adjustments by the stroke subjects are not as distinct and need to be improved to reach normal levels.

It is interesting to compare these results with those of Binkofsky et al [37~~29~~] who found that patients with good recovery and with lesions particularly involving the anterior bank of the intraparietal sulcus, demonstrated poor control of grip aperture, including poor preshaping in the acceleration phase, increased aperture in deceleration phase, increased variability of grip aperture, and a later percentage time of maximum grip aperture compared to controls. In contrast, the present group of patients with paretic movements, and with more generally defined lesions of the parietal cortex, had the necessary degree of control to adjust grasp for both object size and movement speed. It is possible that the present group of patients did not have lesions of the anterior bank of the intraparietal sulcus, since the ability to adjust for size and speed implies an ability to perform preshaping in acceleration and deceleration phases and adjust time of maximum grip aperture.

The neuronal pathways involved in planning and controlling reach-to-grasp are only partially understood, but the posterior parietal cortex [4, 5], area 6 of the premotor cortex [38 39], prefrontal cortex [39] and the cerebellum [40] are involved. These neuronal pathways were apparently functioning to some extent in our patient group.

A limitation of the study was that the number of repetitions the patients could perform were relatively small compared to studies of normal motor control. Also, having more exact information from magnetic resonance imaging of the site and size of the lesions would have allowed greater understanding of the coordination problems of different patients. Future research should aim for larger sample sizes of homogenous patients to increase generalizability. The coordination patterns of patients with different areas of brain damage need to be compared to see if their problems are the same, or different.

To summarise, the performance of this group of patients with a moderate amount of functional recovery did show some similarities to normal subjects in their ability to respond to changes in speed and cup size and in temporal coupling of grasp and transport. Like normal subjects, they were able to increase maximum aperture for faster movements, and had a shorter deceleration phase and time after maximum aperture for faster movements. They could also increase maximum aperture size for a larger object. However, compared to normal subjects, their movements were slower and the deceleration phase was longer. The shorter deceleration phase and time after maximum aperture for faster movements were not as marked as that of normal subjects. Their movement duration increased for the larger cup and their movements were more variable. Also, the temporal coordination of grasp and transport was not as tightly coupled.

Several suggestions for therapy arise from our results. Firstly, patients should practice tasks which involve the use of grasp and transport together, where possible, to necessitate activation of temporally linked central commands for arm and hand. Secondly, since the start of transport and grasp are not as tightly coupled as in controls, practice could concentrate on planning and executing the two components together and not leaving the opening of the hand until it nears the object [19].

To further develop ability to time grasp and transport components appropriately in faster movements, reach-to-grasp could be practised at different speeds and with different size objects, with an emphasis on achieving grasp of larger objects, which appear to be more difficult for them. These suggestions are more specific than those usually described in conventional physiotherapy, being targeted at the timing of reach-to-grasp in particular and so have the potential to improve the effectiveness of training of this aspect of upper limb function. Further research is required to examine whether this potential can be realized.

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