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A novel tool for characterising upper limb function in progressive Multiple Sclerosis through kinematic assessment

Abstract

Introduction: Current upper limb assessment methods in MS rely on measuring duration in tasks like the nine-hole peg test (9HPT). Kinematic techniques may provide a more useful measure of functional change in clinical and research practice. The aim of this study was to assess upper limb function prospectively in people with progressive MS using a kinematic 3D motion capture system and compare with current measures.

Methods: 42 people with progressive MS (PwPMS) and 15 healthy controls reached-and-grasped different objects whilst recorded by a kinematic assessment system. 9HPT, Expanded Disability Status Scale (EDSS), and patient reported outcome measures (PROs) were collected. All measures were taken at baseline for PwPMS and controls, and again at six months for PwPMS.

Results: Relative to controls, PwPMS had significantly longer reaction (0.11s, $p<0.05$) and reach (0.25s, $p<0.05$) times. PwPMS took longer to pick-up (0.34s, $p<0.05$), move (0.14s, $p<0.05$), and place (0.18s, $p<0.05$) objects. PwPMS had lower peak velocities when reaching (7.4cm/s, $p<0.05$) and moving (7.3cm/s, $p<0.05$) objects. Kinematic assessment demonstrated consistent differences between PwPMS with mild and severe upper limb dysfunction as defined by PROs, which were not captured by 9HPT or EDSS in this group. PwPMS demonstrated altered grip apertures profiles, as measured by their ability to complete individual parts of the reach and grasp task, between the baseline and follow-up timepoints.

Conclusions: We have created and tested a novel upper limb function assessment tool which has detected changes and characteristics in hand function, not currently captured by the EDSS and 9HPT.

Keywords – upper limb function, prehension, kinematics, patient reported outcome measures

Manuscript

1. Introduction

Upper limb dysfunction has been found in up to 60% of people with MS (PwMS) at the time of diagnosis and increases in prevalence throughout the disease course (reaching up to 81% at 15 years post diagnosis, based on population registries) (1). The presence of upper limb dysfunction reduces self-reported activities and social participation by 35% in people with MS (PwMS), and impacts employment (2,3). The 9HPT is the current gold standard measure of upper limb function in PwMS, with a singular time parameter derived from an average score from both hands (4). Whilst the 9HPT measures the capacity to complete a task, the actual performance on the task is not recorded. PwMS may take longer to complete the 9HPT due to difficulties with tremor, co-ordination or weakness, which are not captured in the overall score. In PwMS who have mild perceived upper limb dysfunction as measured by their patient reported outcome measures (PROs), capacity measures like the 9HPT, do not accurately capture this impairment (5)Post-hoc analysis of phase 3 trials in secondary progressive MS (SPMS) have shown that the 9HPT shows a small rate of change over time, and a comparatively large difference between confirmed and unconfirmed progression (6). This suggests that the 9HPT is more prone to fluctuation and less robust than other outcome measures, like the timed 25-foot walk test when measuring ambulation, for example. There is a need to explore the clinical utility of more granular outcome measures. Kinematic assessment is the measurement of how a task is performed through the use of instrumental motion capture techniques (7). This allows extraction of granular details such as limb velocity, acceleration, jerk, and spatial path. In recent years, kinematic studies of upper limb function in pwMS have revealed pathological aspects of reaching and grasping, such as increased action tremor (8,9).The primary aim of our study was to use kinematic assessment techniques to quantify upper limb function in a cohort of PwPMS, compared to healthy controls. In the cohort of PwPMS in this study a further aim was to compare the measures delivered by the kinematic assessment techniques to established clinical outcome measures like the 9HPT, EDSS and PROs.

2. Methods

2.1 Standard Protocol Approvals, Registrations, and Patient Consents

This observational prospective cohort study received ethical approval from the UK National Research Ethics Committee (REC) and from the Health Research Authority in November 2019. The study also received approval from the local Research and Innovation department of Leeds Teaching Hospitals NHS Trust. The study has been registered on clinicaltrials.gov (NCT04283071). Written informed consent was obtained from all participants prior to entry in the study.

2.2 Participants and eligibility criteria

Forty-two people with progressive MS were screened and recruited from local MS outpatient clinics, with an a priori target sample of forty, based on sample numbers in previous kinematic studies in MS (10–14). Inclusion criteria included a confirmed diagnosis of primary or secondary progressive MS with disease progression for at least twelve months, and a self-report of impaired hand function. People with relapsing-remitting MS were excluded to limit the impact of relapses on baseline and follow-up assessment. Furthermore, this study was not powered to account for any confounding with progression independent of relapse activity that can be seen in relapsing-remitting MS (15). Fifteen healthy controls were also recruited from the healthy ageing research volunteer pool in the School of Psychology, University of Leeds. Demographic information is shown in Table 1. Exclusion criteria for the controls and PwPMS were the presence of any cognitive impairment or comorbid conditions that could affect upper limb function e.g., previous stroke. For the MS group, PwPMS were interviewed, and clinical healthcare records reviewed to identify any evidence of cognitive dysfunction. Cognitive dysfunction was noted if there was a self-report by PwPMS during their clinical reviews in the previous two years, or evidence of neuropsychological testing documenting cognitive dysfunction. A cognitive screening test was not mandatory prior to entry into the study. PwPMS who were not able to complete the 9HPT with both hands were excluded.

2.3 Kinematic assessment protocol

The kinematic assessment is composed of reach-to-grasp (prehension) trials where each participant picked up and moved objects across an event detection kit (EDK) on the table in front of them. The four cylindrical 3D-printed objects were five cm in diameter to mimic the size of everyday items. Each object had a 1 cm or 3 cm grasping surface size, and a hole in the base of 1 cm or 2 cm (base hole diameter). This base hole was not visible to the participant as it was on the underside of the object. The set-up for the kinematic assessment and objects used are illustrated in Figure 1. The participants were instructed to grasp and move the objects using a precision grip to standardise the grasping parameters. The precision grip, also known as the pincer grip is formed by the thumb and fore-finger opposition. The EDK was constructed with pre-set distances and pegs which were used as landmarks for the objects. Prior to the trials, the participant was allowed a single test trail, which was not part of the trial data, to ensure they understood the movements involved. The start of each trial was triggered by a green light on the EDK, after which the participant moved their hand from a pre-set starting position, reached for the object (reach phase) and then moved it to its final location which involved aligning the base hole of the object over the peg (move phase). A single trial would last a few seconds in total. Object lift and place time stamps were captured by the EDK using copper contact strips on the EDK surface and underside of the objects, connected to a Raspberry Pi 3B+ microcomputer, used to collect the time stamps of these events. A Boxed Infrared Gross Kinematic Assessment Tool (BIGKAT) was also used to track the participant's hand throughout the movement. BIGKAT is an optical motion capture system, which records the movements of infrared light emitting diodes (IREDs) in three-dimensional (3D) space by triangulating images from a pair of infrared cameras (Raspberry Pi PiNoir Cameras), captured at 60Hz. These cameras are controlled by separate Raspberry Pi 3B+ microcomputers which work in synchrony with each other as a single stereo pair for the triangulation of the point source, in this case the IREDs, in 3D space. 3D data points can then be further analysed offline to extract useful output measures to quantify movements. For example, in a prehension movement, the speed and distance travelled by each IRED can be extracted. In the reach and grasp trials in this study, the participants had three IREDs affixed to their hand; one each on the tip of the forefinger and thumb and a third on the radial aspect of the wrist. The kinematic parameters extracted from each trial are illustrated and defined in Figure 2.

2.4 Study design

Baseline demographics and handedness were collected in the patient and control groups. Handedness was determined by the Edinburgh handedness inventory – short form. Participants then performed the 9HPT twice with each hand and undertook the kinematic assessment protocol. This included five consecutive reaching and grasping trials with each of the four objects in a randomised order with each hand, providing a total of 40 trials with each participant, with each trial taking two to three seconds based on initial control testing. In the MS cohort the EDSS was then administered, along with PROs, which included the ABILHAND and Arm Function in Multiple Sclerosis Questionnaire – Short Form (AMSQ-SF) questionnaires (16–18). The AMSQ-SF is a 10-item questionnaire, each of which uses a graded response model to score the respondent on the extent of limitation of their ability to do tasks in the previous two weeks. The raw score ranges from 10 to 60 with a lower score demonstrating better perceived hand function. The ABILHAND- chronic stroke questionnaire was used in this study. It is a 23-item questionnaire, each of which uses a 3-point scale to score the respondent on bimanual activities with a raw score from 0 to 56, and a higher score indicating better hand function. The ABILHAND raw score was used in the analysis. The MS group completed a follow-up assessment (with all baseline measures repeated) six months after the baseline assessment to quantify any changes in upper limb function as the six-month interval is commonly used to assess progression in clinical studies in MS.

2.5 Statistical analysis

The kinematic data were extracted from BIGKAT and the EDK using Python programming scripts. The clinical and kinematic data were combined, validated, and analysed using R studio (version 1.4.1106). For the baseline timepoint of the study, the independent variables of interest in the prehension task were participant group (MS, control), handedness (preferred, non-preferred), object grasp surface size (1cm, 3cm) and object base hole diameter (1cm, 2cm). This produced a 2 x 2 x 2 x 2 design. A series of mixed analyses of variance (ANOVAs) were used to test for statistical significance, which was set at an alpha of 0.05, after applying Levene's test for equality of variances. Due to the focus of this study, only interactions involving group were investigated further with pairwise comparisons. For the MS group, the six-month follow-up delivered one additional independent variable of interest, namely timepoint (baseline, follow-up). Categorical demographic and clinical data between participant groups were compared using Chi-squared test or Fisher's exact test. Continuous

variables were correlated using Spearman's rank correlation coefficient to explore the relationship between the kinematic and clinical parameters, as our results we not normally distributed.. One-way ANOVA was used to compare PRO categories with kinematic and clinical parameters. There was no exclusion of outliers in the statistical analysis.

2.6 Data Availability

Anonymised study data and the R code used for analysis of the data will be made available to any researcher who provides a methodologically sound study proposal to the corresponding author. Individual participants will not be identifiable in any released data, and all appropriate information governance protocols will be followed.

3 Results

3.1 Baseline results

Baseline demographic and clinical data of the forty-two MS participants and fifteen healthy controls are outlined in Table 1. In the MS group there were thirty-three participants with Secondary progressive MS (SPMS) and nine participants with Primary progressive MS (PPMS). The median EDSS of the MS group was 6.5 (range 5.0 - 7.5). The MS group completed the 9HPT with the preferred hand within a mean time of 33.6 (SD 13.5) seconds, compared to the control group who completed it within a mean time of 21.3 (SD 2.1) seconds. There was a significant mean difference between the two groups of 12.3 seconds ($p<0.05$). When testing the non-preferred hand, the PwPMS completed the 9HPT within a mean of 40.4 (SD 16.8) seconds, compared to the control group time of 22.5 (SD 4.4) seconds. There was a significant mean difference between the two groups of 17.9 seconds ($p<0.05$).

3.2 Kinematic parameters

The mean values of the kinematic parameters between the control and MS groups are illustrated in Figure 3 and the effect sizes of the main effects and interactions are outlined in Table 2.

The MS group took significantly longer than controls to react to the start of the trial. The MS group took significantly longer in both the reach and move phases of the trials compared to controls. The MS group also demonstrated significantly lower peak wrist velocities compared to the control group, in each phase. The peak wrist velocity when reaching was significantly

slower with the non-preferred hand in the MS group. The maximum grip aperture when reaching for the objects did not differ significantly between the MS and control groups.

When analysing the time taken to pick-up the objects, there was a significant interaction between group and grasp surface size: both groups took significantly longer to pick-up the objects with the smaller grasp surface size compared to the larger grasp surface size, and the MS group took significantly longer than the control group to pick up objects with both large and small grasp surface sizes. Furthermore, there was a significant interaction between group and hand with the MS group taking significantly longer than the control group to pick-up objects with both their preferred and non-preferred hands.

The time taken to place the objects in their final position was also measured. The MS group took significantly longer than the control group to place the objects, and both groups took longer to place the objects with the smaller base hole diameter compared to large.

3.3 Kinematic parameters correlate with the 9HPT and PROs but not the EDSS.

The participants' scores in both the MS and control group on the 9HPT correlated with a number of the prehension task kinematics measures recorded by the EDK and BIGKAT. There was a significant positive correlation between performance on the 9HPT and the reaction ($r=0.30$, $p<0.05$), reach ($r=0.63$, $p<0.01$), and move times ($r=0.78$, $p<0.01$) on the EDK, suggesting that participants who took longer to complete the 9HPT, also took longer on all aspects of the prehension trials. There was a significant negative correlation between time taken to complete the 9HPT and the peak wrist velocities during the reach ($r=0.69$, $p<0.01$), and move ($r=0.59$, $p<0.01$) phases of the prehension task trials; participants who took longer to complete the 9HPT had significantly lower peak wrist velocities.

Median ABILHAND and AMSQ-SF scores are outlined in Tabe 1.PwPMS who scored worse on the AMSQ-SF took longer to place ($F(2,38) = 4.25$, $p<0.05$) and move objects ($F(2,38) = 3.53$, $p<0.05$) as measured by the EDK. PwPMS who scored worse on AMSQ-SF also took longer to slow down their hand (deceleration time) when reaching for the objects ($F(2,38) = 4.72$, $p<0.05$) and took longer to complete the 9HPT ($F(2,38) = 4.75$, $p<0.05$). There was no significant main effect of the ABILHAND PRO on the kinematic parameters or 9HPT.

There was no correlation between the kinematic parameters and EDSS score in PwPMS. The correlation between the mean 9HPT score of both hands and EDSS was not significant ($r(39)= 0.24$, $p=0.12$).

3.4 Six-month follow-up results

Forty-one out of forty-two patients from the MS group completed the follow-up assessment at an average of 6.8 months (SD 0.7) after the baseline assessment. Twenty nine percent (29%) of participants demonstrated worsening in their EDSS score, based on a 1 point increase in an EDSS < 6.0 and 0.5 point increase in EDSS ≥6.0 (19). Four PwPMS showed a greater than 20% worsening in their 9HPT score (20). However, there was no significant difference in the median EDSS, or mean 9HPT scores and PRO measures between the baseline and follow-up assessment. There were no relapses reported during the study by any of the PwPMS. The 4 participants who showed a >20% worsening at NHPT didn't all show a worsening in EDSS, or PROMS, but in their kinematic measures. However, four participants were too few to make any statistical analysis of this subgroup meaningful.

The differences in the kinematic parameters between baseline and follow-up in the MS group are shown in Table 2. When compared to the baseline assessment, PwPMS demonstrated similar results in the reaction, reach and move times at six months. PwPMS demonstrated a significantly smaller maximum grip aperture and achieved this grip aperture earlier at follow-up compared to baseline.

4 Discussion

The aim of our study was to compare a novel kinematic assessment tool between PwPMS and healthy controls, and in the PwPMS group to compare the tool to current clinical measures and PROs. At baseline, the MS group demonstrated a wide variation in upper limb dysfunction compared to the control group who displayed expected reach and grasp profiles in line with previous studies of healthy adults (21,22). The MS group demonstrated increased reaction times at task initiation which has been shown to be a marker of cognitive impairment despite the group showing no symptoms of cognitive impairment (self-reported or evidenced in clinical records) (23). This increase in reaction time for tasks has been shown previously in PwMS due to attention deficit and possible subclinical motor slowing (24) . The MS group also demonstrated significantly longer object pick-up and placement times. This is in keeping with

studies which have shown increased variation in grip force control in PwPMS, negatively affecting manipulation of objects (8,25). In addition, an instrumented version of the Action Research Arm Test has previously shown that PwMS take significantly longer in the movement and manipulation of objects, correlated to the level of physical impairment (26). The time taken for the placement of the objects on the peg was also determined by the size of its base hole diameter. Both the control and MS group took longer to line up the objects with the smaller base hole diameter with the peg. The importance of somatosensory feedback for object placement in the absence of visual feedback has been demonstrated before in healthy adults, and the significantly longer placement time for the MS group demonstrates the impairment in this central network (which has been localised to abnormal thalamic resting state functional connectivity) (27,28). The significantly slower peak wrist velocities when reaching for and moving the objects seen in the MS group compared to controls may be the result of impaired muscle activation patterns (found previously in pwMS with these abnormal muscle synergies increasing in more advanced disease as defined by an EDSS of greater than 6.0) (29,30).

We have demonstrated the importance of hand preference in the MS group, with significantly worse performance in the non-preferred hand in almost all the kinematic parameters compared to controls. This finding reinforces the asymmetric nature of upper limb dysfunction in PwPMS. Previous studies which used the 9HPT as an outcome measure have shown that the inter-hand asymmetry increases in PwPMS who have an EDSS greater than 6.0 (31,32). This asymmetry in prehension in PwPMS may in turn reflect the asymmetry in corticospinal excitability seen during transmagnetic stimulation in PwPMS (33). This shifting of hemispheric excitability predicts the severity of MS-related physical and objective cognitive symptoms. Although the 9HPT in our cohort of PwPMS identified this inter-hand asymmetry, the kinematic assessment demonstrated that the asymmetry exists across multiple aspects of the reach and grasp movement including peak wrist velocities and object pick-up.

Interestingly, the maximum grip aperture when reaching for objects remained similar between both groups despite the significant differences between the MS and control group in many aspects of the reach and grasp trials. This contrasts with the significantly smaller maximum grip aperture demonstrated by people with Parkinson's disease (PD) compared to

healthy controls when reaching for objects, likely due to the hypometric movement features that are typical for individuals with PD (34).

The kinematic parameters and the 9HPT showed greater correlation with the AMSQ-SF PRO compared to the ABILHAND PRO in our cohort, which may be due to the development and validation of the AMSQ-SF specifically for pwMS (35). This correlation also demonstrates that kinematic performance can reflect perceived function (and has been demonstrated previously in grasping tasks in pwMS) (36). The kinematic parameters at baseline showed a significant correlation across the parameters and currently accepted clinical outcomes, namely the 9HPT. However, the 9HPT provides a singular measure of capacity, namely a time parameter, and correlates more closely with perceived performance than actual performance when compared to kinematic techniques (37). Furthermore, the significantly longer reaction times we identified would affect performance on the 9HPT, but the overall 9HPT score is unable to capture this aspect of performance. A virtual version of the 9HPT previously tested in PwMS has demonstrated these changes in smoothness and speed of movement in PwMS in comparison to healthy controls. These findings provide an explanation for the scores seen in the standard 9HPT (38). With regards to the EDSS, the wide variation in 9HPT scores and kinematic parameters across a narrow EDSS range of 5.5 to 7.0 in our MS cohort reinforces the inability of the EDSS to adequately capture upper limb function in its scoring.

In the follow-up phase, the smaller maximum grip aperture and shorter time to reach maximum grip aperture has not been previously identified. In the stroke population, inaccurate scaling of maximum grip aperture and decoupling of the spatio-temporal coordination between the hand and grasping has been similarly shown (39). It is difficult to know if these changes in grip aperture in our MS cohort at follow-up are clinically meaningful with regards to perceived hand function. These findings may highlight grip aperture as a possible early sign of change in grasping function in PwPMS.

The clinical utility of these kinematic measures in pwMS has been shown in recent studies which have used these techniques to measure change in upper limb spasticity in a cohort of pwMS after treatment with nambiximols (40). A more recent study shows that a short course of immersive virtual reality training is able to improve speed and stability of hand-to-mouth movements in pwMS with upper limb dysfunction (41). The portability of the kinematic assessment toolkit in our study allows this technique to be deployed in the clinical

environment relatively easily. Furthermore, with the commencement of new trials specifically in the progressive MS population e.g., Cladribine to Halt Deterioration in People with Advanced Multiple Sclerosis (ChariotMS – NCT04695080) and Optimum Clinical Trial Platform for Progressive MS (OCTOPUS - ISRCTN14048364), clinicians could use this tool to objectively and precisely measure upper limb function, providing long term data on disease progression.

Our study had some limitations, primarily the use of older control participants, who were not matched to PwPMS in terms of age. Ageing affects kinematics of reach and grasp in the healthy population with older adults demonstrating longer reach and grasp times and slower peak wrist velocities compared to younger adults (42). However, despite being significantly older, the kinematic assessment protocol was still able to detect significant differences between the MS and control group, which suggests that these differences might be more pronounced in a younger age matched control group. Our study has been conducted in a defined progressive MS cohort, and therefore the relevance of these changes in upper limb function in relapsing-remitting MS need further clarification. The lack of a follow-up data-point for the control group was another limitation, but as this study was carried out during the peaks of the COVID-19 pandemic, 10 out of 15 of the control participants were reluctant to attend hospital for repeat visits. Finally, the lack of a cognitive battery at initial screening was a limitation as we were unable to quantify the extent of any subclinical cognitive impairment in our MS group, although we limited this by screening for any evidence of self-reported or clinically reported cognitive dysfunction. However, the demonstration of significantly increased reaction times in our MS group highlights the potential sensitivity of kinematic assessment in detecting possible early cognitive slowing in this cohort.

Future work will involve follow-up of a larger number of PwPMS in the clinical space for longer timepoints at 12 and 24 months, as well as testing in the relapsing MS population. This will provide further insights into the impact of relapses on upper limb function.

5 Conclusions

The kinematic assessment of upper limb function in this study has provided novel insights into the multifaceted aspects of upper limb impairment in people with progressive MS. The kinematics reflect perceived function on patient reported outcome measures. The inclusion

of progressive PwPMS allowed us to explore the variation in upper limb performance and demonstrate the importance of object parameters on grasping in this clinically well-defined group. We were also able to detect altered grip aperture profiles after six months of follow-up which highlights grip aperture as a possible early indicator of grasping performance in PwPMS. Simple modifications to this kinematic assessment protocol can expand its use in the evaluation of upper limb dysfunction in the natural history, treatment, and rehabilitation of PwPMS.

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Disclosures

The authors do not have any disclosures to report.

Tables

Table 1. Demographics and clinical characteristics of the patient and control group at baseline

		Patient (n = 42)	Control (n = 15)	Mean Difference (95% CI), p-value
Age, years (SD, range)		55.2 (6.5, 39 - 67)	71.5 (3.0, 66 - 77)	16.2 (12.9, 19.9), p<0.05
Gender (M : F)		12 : 30	3 : 12	Chi-squared = 0.42 (p = 0.734)
Handedness (L : R)		10 : 32	1 : 14	Chi-squared = 2.08 (p = 0.253)
Disease specific characteristics of the patient group at baseline				
MS subtype	PPMS (number of participants)			9
	SPMS (number of participants)			33
Disease duration*, years (SD)				20.6 (8.92)
Time since SPMS diagnosis, years (SD) (for SPMS cohort of 33)				5.1 (3.97)
Age at SPMS diagnosis, years (SD)				50.3 (7.97)
Time since PPMS diagnosis, years (SD) (for PPMS cohort of 9)				14.4 (8.13)
Age at PPMS diagnosis, years (SD)				49.9 (7.72)
Median EDSS for full cohort of 42 (range)				6.5 (5.0 – 7.5)
Median ABILHAND score (range)				28 (8 – 46)
Median AMSQ-SF score (range)				23 (10 – 55)

*Denotes the time period since the patient first experienced neurological symptoms, that were subsequently attributed to their MS, rather than the time period since clinical diagnosis, for both the PPMS and SPMS cohort combined†

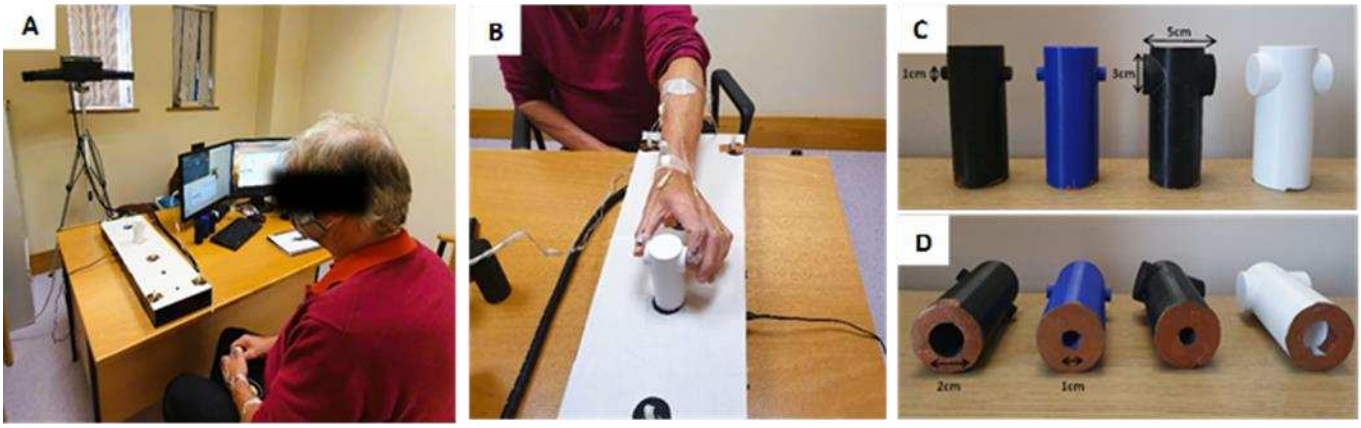
Table 2. The main effects and interactions of the kinematic parameters at baseline and follow-up

Dependant kinematic variable	Baseline (MS vs Control group)		Follow-up (Baseline vs Follow-up; MS group only)	
	Main effect / Interaction	**F(d.f.) = F-value ; $\eta_p 2$; p-value**	**Main effect**	**F(d.f.) = F-value ; $\eta_p 2$; p-value**
Reaction time	Group	F(1,53) = 9.42; 0.15; 0.003	Time point	F(1,80) = 0.35; 0.00; 0.555
Time spent in reach phase	Group	F(1,53) = 6.37; 0.11; 0.015	Time point	F(1,76) = 2.20; 0.03; 0.142
Time spent in move phase	Group	F(1,53) = 4.11; 0.07; 0.048	Time point	F(1,78) = 0.18; 0.00; 0.672
Object pickup time	Group	F(1,51) = 9.18; 0.15; 0.004	Time point	F(1,78) = 0.62; 0.00; 0.439
	Grasp surface size	F(1,260) = 60.6; 0.19; <0.001	Grasp surface size	F(1,405) = 165; 0.29; <0.001
	Group x Grasp surface size	F(1,260) = 3.91; 0.01; 0.048	Hand	F(1,428) = 7.74; 0.02; 0.006
	Group x hand	F(1,267) = 5.28; 0.02; 0.022		
Object placement time	Group	F(1,47) = 15.2; 0.25; <0.001	Time point	F(1,64) = 0.77; 0.01; 0.384
	Base hole diameter	F(1,258) = 76.5; 0.23; <0.001	Base hole diameter	F(1,408) = 76.7; 0.16; <0.001
	Group x Base hole diameter	F(1,258) = 5.16; 0.02; 0.024		
Maximum wrist velocity when reaching objects	Group	F(1,50) = 9.06; 0.15; 0.004	Time point	F(1,77) = 0.06; 0.00; 0.812
	Hand	F(1,261) = 6.04; 0.02; 0.015		
	Group x Hand	F(1,261) = 9.55; 0.04; 0.002		
Maximum wrist velocity when moving objects	Group	F(1,51) = 4.99; 0.09; 0.030	Time point	F(1,77) = 2.33; 0.03; 0.131
			Hand	F(1,410) = 7.62; 0.02; 0.006
Maximum grip aperture (MGA)	Group	F(1,49) = 0.161; 0.003; 0.690	Time point	F(1,71) = 9.71; 0.12; 0.003
	Grasp surface size	F(1,254) = 5.27; 0.02; 0.023	Grasp surface size	F(1,389) = 32.8; 0.08; <0.001
	Hand	F(1,259) = 6.39; 0.02; 0.012	Hand	F(1,402) = 8.26; 0.02; 0.004
Proportion of reach time to achieve MGA	Group	F(1,50) = 0.08; 0.00; 0.772	Time point	F(1,74) = 4.27; 0.05; 0.042
			Grasp surface size	F(1,401) = 9.35; 0.02; 0.002

$\eta_p 2$ effect size reported as partial Eta squared

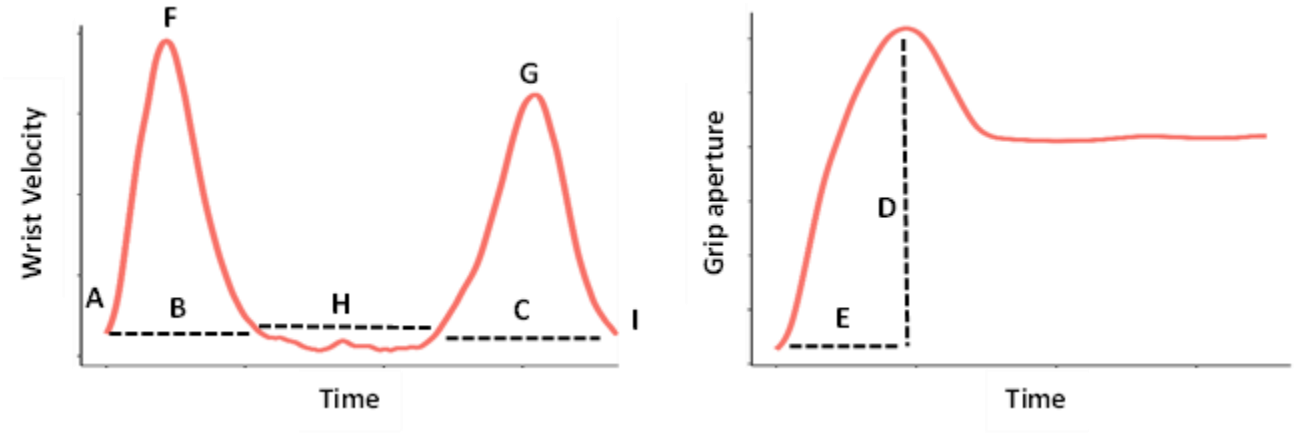
Figures

Figure 1. Kinematic assessment set-up with BIGKAT and the EDK, and the objects used in the trials.



A) Equipment set-up for the kinematic assessment protocol with the participant sitting at a desk with BIGKAT placed opposite them on the other side of the desk and the EDK placed on the desk in front of them. The investigator operates the computer next to the participant during the trials. B) Sample trial as recorded from BIGKAT's point of view with the participant reaching for an object on the EDK. C) The cylindrical objects used for the kinematic assessments include four objects, each with a width of 5 cm between the two grasp surfaces. Two of the objects have a 1 cm grasp surface diameter. Two objects have a 3 cm grasp diameter. D) The bottom of two objects has a 1 cm diameter hole, to allow the object to be placed on the corresponding peg on the event detection kit, which are just less than 1 cm in diameter. The other two objects have a 2 cm diameter base hole diameter. The two-sided copper tape on the bottom of the objects allows the event detection kit to pick up the contact of the object once it is placed on a peg. Written consent obtained for inclusion of participant picture in figure.

Figure 2. Sample wrist velocity and grip aperture profiles from the reach and grasp trials and the main kinematic parameters extracted.



A. Reaction time – time from when the green light on the EDK lights up to the time when the participant stops holding down the start button, indicating they have started moving their hand.

B. Reach phase –time taken to reach the object from the starting position, measured as the time period between which the wrist velocity becomes greater than 5cm/s at the start position and then reduces below 5cm/s for the first time at the object position.

C. Move phase – the time period from when the wrist velocity goes above 5cm/s once the object has been picked up to the next time when the wrist velocity decreases below 5cm/s.

D. Maximum grip aperture – the maximum distance between the tip of the thumb and forefinger during the trial which occurs sometime during the reach phase when the participant is reaching for the object.

E. Time to maximum grip aperture – the time from the start of the movement to the time of maximum grip aperture

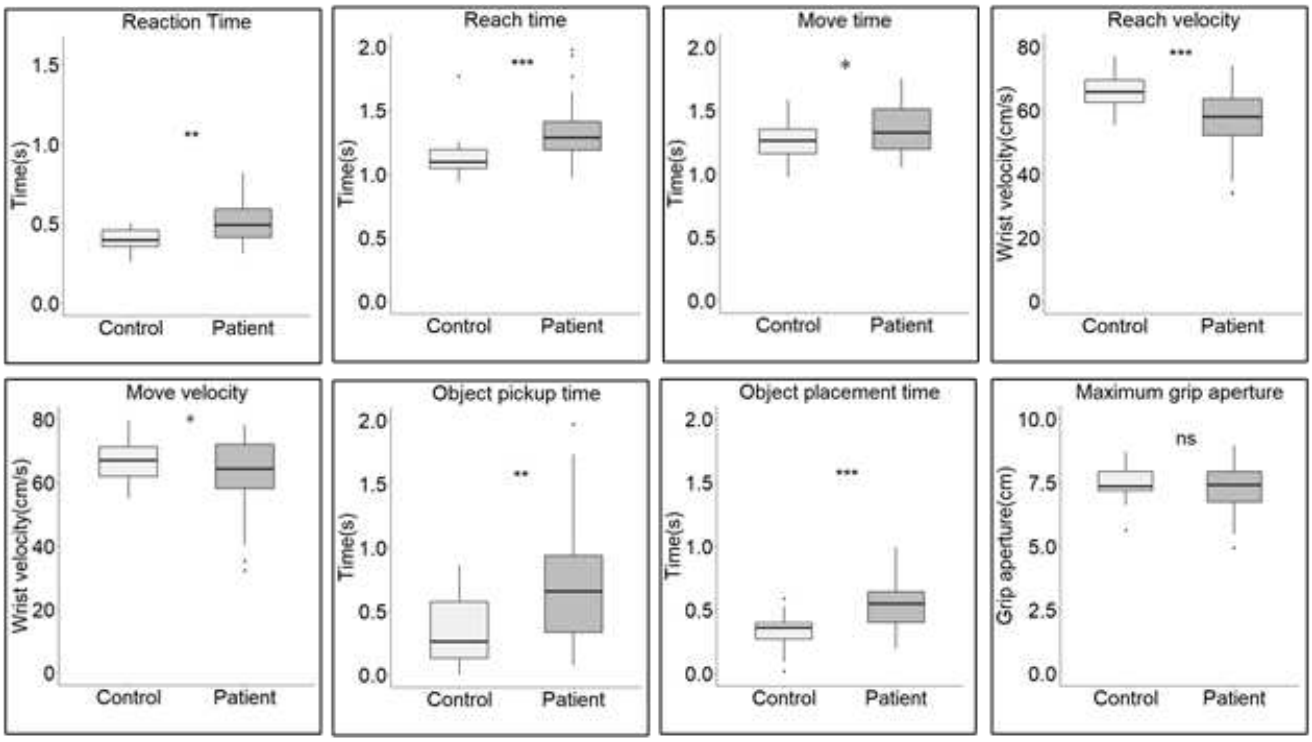
F. Maximum wrist velocity (reach phase) – the maximum wrist velocity when the participant is reaching for the object during the reach phase.

G. Maximum wrist velocity (move phase) – the maximum wrist velocity when the participant is moving the object from its start position to the end position during the move phase.

H. Object pick-up – the time taken for the participant to pick up the object. This phase comes immediately after the reach phase and is just before the move phase. The wrist velocity in this phase is below the 5cm/s threshold, indicating the participant is attempting to pick up the object.

I. Hover phase – the time taken for the participant to place the object on the peg on its end position on the kit. This phase is at the end of the trial and this time period was determined as the period of time from when the wrist velocity reduced below 5cm/s at the end of the move phase to the time at which the object made contact with the contact-point on the EDK.

Figure 3. Mean of kinematic parameters in patients and controls at baseline assessment



* p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001, ns = non-significant. Reach and move velocity graphs illustrate the maximum wrist velocity recorded during the reach and move phases of the trial. MGA, maximum grip aperture

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