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AGE-RELATED DIFFERENCES IN UPPER LIMB PROPRIOCEPTIVE ACUITY [1, 2]

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Summary.—Although upper limb movements are known to be slower and more variable in elderly persons, the extent to which these changes are associated with deficits in movement-related sensory feedback is poorly understood, despite the importance of proprioception in the control of skilled movement. Age-related changes were examined with 22 participants (10 of *M* age 27 years and 12 of *M* age 75 years) in performance of an elbow position-matching task which varied in terms of interhemispheric transfer and/or the need to retrieve memory-based proprioceptive information. Matching errors were significantly greater, and movements more prolonged, and irregular in their time course in the elderly group than in the young group. Impaired performance in conditions requiring interhemispheric transfer and retrieval of memory-based proprioceptive information reflected the importance of cognitive processing during complex sensorimotor tasks. This novel matching paradigm provided a sensitive means of manipulating the demands of the task and may be an effective method for as sessing both cognitive and sensorimotor declines associated with aging.

Changes in motor performance with aging frequently include slowed and variable reaction and movement times (Welford, 1959; Spirduso, 1975). Irregular movement trajectories associated with visually guided reaching tasks have also been observed (Darling, Cooke, & Brown, 1989; Brown, 1996; Seidler-Dobrin, He, & Stelmach, 1998). Further, decreased postural stability (Woollacott, Shumway-Cook, & Nashner, 1986; Alexander, Shepard, Gu, & Schultz, 1992) and impaired locomotor function contribute to the loss of functional independence and increased reliance on home-care services (Sakari-Rantala, Heikkinen, & Ruoppila, 1995). Considerable research supports the view that sarcopenia, defined as a loss of muscle mass and strength that occurs with age, and degeneration of movement-related brain areas also contribute to a decline in voluntary movement. For example, the cerebellum, which plays an important role in motor planning and execution, undergoes significant age-related degeneration of both white (Jernigan, Archibald, Fennema-Notestine, Gamst, Stout, Bonner, & Hesselink, 2001) and grey (Sjobeck, Dahlen, & Englund, 1999) matter. In contrast, the extent to which

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changes in movement-related somatosensory information plays a role in impaired motor performance in older individuals has not been extensively examined.

Feedback from muscle, tendon, joint, and cutaneous receptors provide proprioceptive information regarding changes in joint position and muscle force. Muscle spindle information which codes for both static and dynamic aspects of limb displacement is considered to be of particular importance in the control and coordination of goal-directed movement. Such information has been found critical in controlling the interactional forces (Sainburg, Poizner, & Ghez, 1993) and limb segment timing (Cordo, Bevan, Gurfinkel, Carlton, Carlton, & Kerr, 1995; Ghez & Sainburg, 1995) during multijoint movements. Proprioceptive feedback is also used to control movement trajectories (Roll, Bergenheim, & Ribot-Ciscar, 2000) and to form a representation of body position used in skilled movement (Kawato & Wolpert, 1998; Naito, 2002). Rothwell, Traub, Day, Obeso, Thomas, and Marsden (1982) and Ingram, van Donkelaar, Cole, Vercher, Gauthier, and Miall (2000) studied individuals with selective loss of large diameter afferent fibers and reported an inability to produce efficient and accurate limb movements in the absence of visual feedback impaired people's ability to learn new motor skills. These studies illustrate the critical role of proprioception in the planning and execution of learned movement.

Most studies examining changes in somatosensory function in elderly persons have focused on the ability to either detect passive motion or reproduce passively determined joint positions in the lower limb (Skinner, Barrack, & Cook, 1984; Pai, Rymer, Chang, & Sharma, 1997; Petrella, Lattanzio, & Nelson, 1997). Increased errors in reproducing knee or ankle positions or delays in detecting passive motion have been taken as evidence of compromised proprioceptive acuity and are thought to contribute to age-related postural instability (Lord, Clark, & Webster, 1991; Fitzpatrick & McCloskey, 1994), impaired locomotor function (Lord, Ward, & Williams, 1996), and the development of osteoarthritis (Sell, Zacher, & Lack, 1993).

Surprisingly, little is known regarding upper limb proprioceptive acuity in older individuals despite the importance of being able to reach, support, and manipulate objects in maintaining functional independence. In two previous studies Kokmen, Bossemeyer, and Williams (1978) did not find age-related differences in detection of changes in alternating flexion and extension movements in metatarsal and metacarpal joints. This is in contrast to Ferrell, Crighton, and Sturrock (1992), who found that older individuals had difficulty in detecting the position of a finger joint compared to younger participants. The purpose of this study was to investigate age-related changes in upper limb proprioceptive acuity. It was hypothesized that older participants would generate greater matching errors, take longer to perform the task, and produce matching movements less smoothly than younger participants. It was further hypothesized that errors would increase with matching-task demands and with the degree of movement displacement. These hypotheses were tested in young and older participants by measuring absolute matching error, movement time, and the number of velocity peaks associated with the matching movement during matching conditions which varied in difficulty and degree of movement displacement.

Method

Participants

Ten young participants (5 women, 5 men; *M* age = 27 yr.) and 12 elderly (8 women, 4 men; *M* age = 75 yr.) were recruited, and all were right-handed as assessed on the Edinburgh inventory (Oldfield, 1971; Riolo-Quinn, 1991). All participants in both groups lived independently in the local community and were free of upper limb neurological and musculoskeletal conditions that might impair task performance. Elderly participants were screened for general health and cognitive functioning by a trained occupational therapist. Self-reports of daily activity in living indicated that all participants engaged in light housekeeping, volunteered, and engaged in social and recreational activities in addition to most driving their own motor vehicles. Participants were paid a nominal fee for their participation. All procedures received approval from the Institutional Human Subjects Review Board at the University of Michigan.

Experimental Design

Participants were blindfolded and seated upright at an adjustable table with their forearms resting on two instrumented manipulanda designed specifically for measuring angular displacement of the elbow joint in the horizontal plane. Each manipulandum consisted of a horizontal rigid metal support adjusted to the length of the subject's forearm to align the center of elbow-joint rotation with the pivot point of the manipulandum. Participants grasped a vertical handle located at the distal end of each support. Standardized start positions for the shoulder (60° abduction, 30° flexion), elbow (80° flexion), and wrist (neutral) joints were maintained across participants.

Three matching conditions, which varied in terms of memory requirements and the need for interhemispheric transfer, were performed for 10° or small, 30° or medium, and 60° or large angular displacements, from a starting position of 80° (180° equal to full extension) as shown in Fig. 1. For 10° movements, the arm was passively extended from 80° to 90°; for 30° movements, the arm was extended from 80° to 110°; and for 60° movements, the arm was extended from 80° to 140°.

Passive extension was followed by passive flexion of the forearm to the

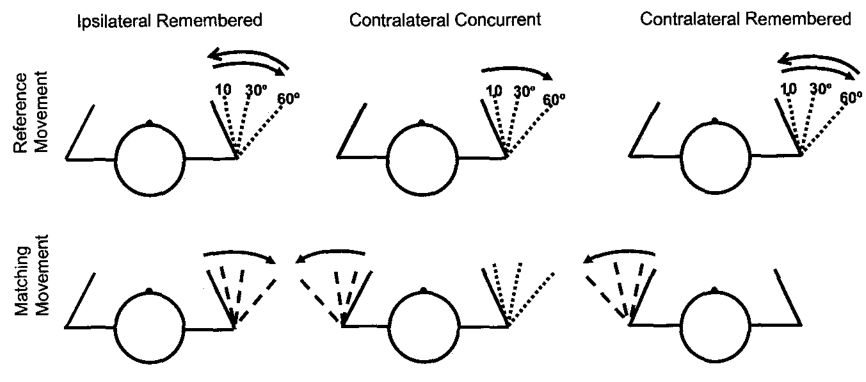

FIG. 1. Schematic of the three elbow position matching conditions as viewed from above the subject. Reference movements of 10°, 30°, and 60° (dotted lines) were passively generated from a standardized start position (solid line). The forearm was either returned to the start position (ipsilateral remembered, contralateral remembered condition) or maintained in the reference position for the duration of the matching movement (contralateral concurrent condition) as indicated by the arrows in the upper panels. The reference movement was reproduced by matching with the ipsilateral or contralateral forearm as shown in the lower panels. Dashed lines indicate 10°, 30°, and 60° matching movements. Arrows indicate direction of the matching movement in each condition.

start position in the case of memory-based matching tasks, or, in case of the contralateral concurrent condition, the forearm remained in the extended position for the duration of the matching task. During ipsilateral remembered matching, participants reproduced the reference movement with the same arm, thereby requiring participants remember the reference position to generate the matching movement. During contralateral concurrent matching, the reference arm was held in the reference position while participants reproduced the movement with the opposite arm. In this condition, continuous feedback about limb position was available, although position information had to be transferred to the opposite hemisphere for matching to occur. Lastly, during contralateral remembered matching, memory-based information regarding the reference position had to be transferred from one hemisphere to the other to produce the matching movement. The average of three trials for each movement displacement (10°, 30°, 60°) and condition (ipsilateral remembered, contralateral concurrent, contralateral remembered) was used for the analyses.

Data Acquisition and Analysis

Elbow-joint rotation was recorded as the voltage output from calibrated precision potentiometers mounted beneath the pivot of each manipulandum. The analog signals were digitized at 50 Hz, low pass filtered (4th order Butterworth, zero phase lag, 6 Hz cut-off frequency) and converted to angular displacement values using custom-designed software (LabVIEW™ National Instruments). Absolute matching error, movement time, and movement smoothness, as reflected by the number of velocity peaks associated with the matching movement were calculated. Movement time was calculated for data from differentiated angular positions utilizing onset and offset values that were 2 *SD*s greater than premovement baseline data averaged over a 200-msec. period. This procedure minimized the influence of any small deviations in static arm position prior to and following the matching movement and allowed for a more conservative measure of movement time. The number of velocity peaks was assessed from the number of zero crossing in the double-differentiated position record of the matching movement divided by two (Brooks, Cooke, & Thomas, 1973; Goble, Lewis, & Brown, 2006).

Statistical Analysis

Mean outcome measurements were separately analyzed using three-way repeated-measures of analysis of variance (standard least squares model) to test for the main effects of age (young and elderly), matching condition (ipsilateral remembered, contralateral concurrent, and contralateral remembered), and movement displacement (10°, 30°, 60°), plus all 2-way and 3-way interactions. When significant main effects were found, multiple and pairwise *post hoc* comparisons were made, using the Bonferroni adjustment procedure.

Results

Absolute Matching Error

A main effect of age on absolute matching error was observed ($F_{1,20}=8.05$, $p=.01$). In both young and elderly participants, matching condition ($F_{2,20}=21.91$, $p<.001$) and movement displacement ($F_{2,20}=14.5$, $p<.001$) also influenced absolute matching error. Significant differences ($p=.001$) were found between small and large and small and medium movement displacements. When considering matching condition, there were significant differences between the ipsilateral and contralateral remembered conditions ($p<.001$) and between the contralateral concurrent and contralateral remembered ($p=.002$) conditions. Mean, standard deviation, and standard error for absolute error for each matching condition and movement displacement are shown in Table 1.

In the younger group, significant differences in absolute matching error were observed between the ipsilateral and contralateral remembered conditions at 10° ($p=.03$; 95% CI, 0.11 to 2.4), with differences at 30° ($p=.06$; 95% CI, –0.19 to 4.5) and 60° ($p=.056$; 95% CI, –0.08 to 5.4) falling short of statistical significance. In the elderly group, errors were greatest in the most demanding matching condition (contralateral remembered) at 60°

TABLE 1
GROUP MEANS, STANDARD DEVIATIONS, AND STANDARD ERRORS FOR ABSOLUTE MATCHING ERROR (DEG.) IN EACH MATCHING CONDITION

Matching Task	Young ($n=10$)			Elderly ($n=12$)		
	M	*SD*	*SE*	*M*	*SD*	*SE*
Ipsilateral Remembered						
10°	1.58	1.1	0.39	3.30	1.6	0.48
30°	3.27	1.5	0.49	4.65	2.4	0.73
60°	3.97	1.7	0.61	5.47	3.6	1.05
Contralateral Concurrent						
10°	2.20	1.6	0.61	3.80	1.7	0.49
30°	4.54	2.3	0.74	5.10	2.3	0.66
60°	5.95	2.5	0.97	6.60	3.6	1.70
Contralateral Remembered						
10°	2.88	1.7	0.50	4.60	3.2	0.93
30°	5.34	1.0	0.87	6.50	3.5	1.00
60°	6.38	3.3	1.40	9.84	4.1	1.20

wherein matching was memory based and required interhemispheric transfer of proprioceptive feedback. Significant differences in absolute matching error occurred between the ipsilateral and contralateral remembered conditions at 10° ($p=.007$; 95% CI, 0.44 to 2.5) and 60° ($p<.002$; 95% CI, 2.6 to 7.7) and between the contralateral concurrent and contralateral remembered conditions at the 60° movements ($p=.02$; 95% CI, 0.37 to 6.39).

In both age groups, absolute matching error increased with the displacement of the reference movement ($F_{2,20}=14.5$, $p<.001$) regardless of task. However, there was a disproportionate increase in absolute matching error for the elderly group compared to young participants when reproducing large angular displacement (60°) reference movements in the contralateral remembered condition.

Movement Time

Mean movement time values are summarized in Table 2 for young and elderly participants. Elderly participants took significantly longer than young participants to perform matching movements ($F_{1,20}=10.75$, $p=.003$). In both young and elderly participants, movement displacement ($F_{2,20}=26.2$, $p<.001$) influenced movement time. As a main effect, matching condition did not influence movement time ($F_{2,20}=1.71$, $p=.20$). Significant differences were found between small and between large ($p=.002$) and small and medium movement displacements ($p=.02$).

Since there were no main effects of movement condition on movement time, movement condition was collapsed across movement displacement. Age-related differences in movement displacement were found when reproducing small (10°, $p=.006$; 95% CI, 0.21 to 1.1) compared to medium (30°,

TABLE 2
GROUP MEANS, STANDARD DEVIATIONS, AND STANDARD ERRORS FOR MOVEMENT TIME (SEC.) IN EACH MATCHING CONDITION

Matching Task	Young ($n = 10$)			Elderly ($n = 12$)		
	M	*SD*	*SE*	*M*	*SD*	*SE*
Ipsilateral Remembered						
10°	1.15	0.48	0.15	2.1	0.94	0.28
30°	2.06	0.58	0.22	2.7	1.30	0.36
60°	2.73	0.24	0.08	2.8	1.00	0.28
Contralateral Concurrent						
10°	1.66	0.60	0.20	3.46	1.76	0.50
30°	2.54	0.78	0.24	3.04	1.38	0.40
60°	3.04	0.28	0.08	3.70	1.48	0.44
Contralateral Remembered						
10°	2.2	1.10	0.38	2.52	1.52	0.48
30°	3.2	0.68	0.22	3.24	0.74	0.20
60°	3.4	0.64	0.20	3.68	1.80	0.52

$p = .003$; 95% CI, 0.24 to 1.0) displacement movements. At 60° ($p = .15$; 95% CI, −0.21 to 1.1), no significant age differences were observed.

For young participants, movement time increased as the displacement of the reference movement increased ($F_{2,8} = 13.4$, $p < .001$) while, for elderly participants, there were no statistically significant differences in movement time across movement displacements ($F_{2,10} = 2.0$, $p = .06$). In other words, elderly participants required almost as much time to match 10° movements as they did to match 60° movements. In both groups movement time increased slightly with increasing task demands as it took longer to perform matching movements in the contralateral remembered than the ipsilateral remembered condition. However, these differences did not reach statistical significance as variability increased. In the contralateral concurrent and contralateral remembered conditions, movement time was also greater for the elderly group than the young group, but these differences were not statistically significant.

Kinematics Associated with Proprioceptive Matching

For young participants, matching movements were relatively smooth and characterized by 1 or 2 velocity peaks (mean number of peaks: $1.9 \pm .13$ *SD*). For the elderly group, however, movements were significantly more irregular in their time course than for young participants ($F_{1,20} = 36.9$, $p < .001$), with the number of velocity peaks ranging from 2 to 5 (mean number of peaks: 3.8 ± 1.2 *SD*). Representative movement profiles for a young and elderly participant are shown in Fig. 2. In both young and elderly participants, matching condition influenced the number of velocity peaks ($F_{2,20} = 3.47$, $p = .03$). Significant differences were found between both the ipsilateral remembered with contralateral concurrent ($p = .02$) and with contralateral remembered ($p = .04$) conditions. No differences in the number of velocity peaks were observed in either age group as a function of movement displacement. In contrast, more complex contralateral concurrent compared to ipsilateral remembered ($p = .004$) and contralateral remembered and ipsilateral remembered ($p = .001$) matching led to a significant decrease in movement smoothness by the elderly group. Such task effects were not seen for young participants ($p > .44$). Typical examples of proprioceptively guided movements are shown in Fig. 2 where individual velocity records obtained in the contralateral remembered condition clearly reflect age-related differences in smoothness of movement.

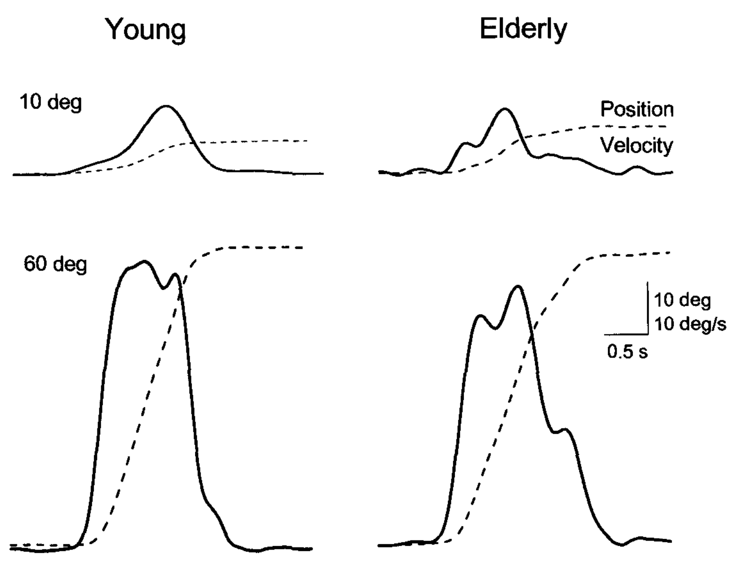

FIG. 2. Individual kinematic records of position (dashed line) and velocity (solid line) associated with matching 10° and 60° contralateral remembered matching movements made by one young and one elderly participant

DISCUSSION

Previous research concerning effects of age on proprioception has focused on the lower limb with little attention to the upper limb. The present study indicated that proprioceptive acuity related to limb position is significantly impaired with age, although the magnitude of matching error depends upon such factors as movement displacement and the demands of the matching condition.

Increasing absolute matching error as a function of movement distance has been observed in both younger and older participants for shoulder position-matching tasks (Zuckerman, Gallagher, Lehman, Kraushaar, & Choueka, 1999), although in an earlier study by Marteniuk, Shields, and Campbell (1972), young subjects showed no differences as a result of movement distance. The underlying mechanism for a distance effect on matching ability may be related to age-dependent muscle stiffness or the range of joint motion. For example, Pickard, Sullivan, Allison, and Singer (2003) reported that accuracy of a hip abduction matching task was greater for older adults when matching movements were generated in the inner versus outer range of the hip joint. It is also possible that the generation of larger matching movements leads to greater error as a result of increased noise associated with larger descending motor commands (Rosenbaum, Meulenbroek, & Vaughan, 2001).

It is unclear whether the increased movement time taken by elderly participants to reproduce the reference movement reflects an attempt to minimize matching error through speed-accuracy trade-off mechanisms or may have actually contributed to matching errors, at least in remembered conditions, as a result of degradation of memory components over time. Movement duration interferes with the persistence of target location in memory and can influence end-point accuracy during proprioceptively guided movement (Adamovich, Berkinblit, Fookson, & Poizner, 1998; Lemay & Proteau, 2001). Also, the greatest group difference in movement time occurred during the matching of small reference movements regardless of matching condition. This may reflect an impaired ability to process minimal differences in proprioceptive discharge associated with small joint displacements which, in turn, would necessitate a disproportionately longer time spent in comparing actual with intended limb position.

In the present study, proprioceptively guided movements made by elderly participants were consistently characterized by several velocity peaks, in contrast to one to three peaks observed by young participants. During comparable, single-joint movements made under visual guidance, irregular movement trajectories have also been described in older individuals with secondary, corrective movements typically occurring during the deceleration phase as the arm approaches the visual target (Goggin & Meeuwsen, 1992; Brown, 1996). In the case of proprioceptively guided movements, discontinuities were observed throughout the movement which may reflect changes in strategy to maximize task performance. That is, elderly participants produced several submovements correlated with an increase in movement time due to a comparison of actual limb position to on-line or remembered proprioceptive information related to the reference position. This apparent change in strategy, however, did not contribute to greater matching accuracy compared to the performance of young participants, suggesting that other factors, such as attention or difficulties in processing proprioceptive information, contribute to age-related declines in awareness of limb position.

The matching paradigm utilized in the present study is unique in that it provided a method by which central processing demands associated with proprioceptive feedback can be varied. Contralateral matching tasks requiring interhemispheric transfer of proprioceptive information were consistently associated with greater errors compared to matching with the same arm regardless of age. However, in contrast to young participants, elderly participants showed greater errors in contralateral matching tasks which also required retrieval of memory-based proprioceptive information concerning the limb-reference position. This observation may be partly explained by age-related deterioration in cognitive processing which is now thought to have the potential to influence sensorimotor function in the elderly significantly (Li & Lindenberger, 2000).

Dual-task paradigms have shown that increased attentional demands are associated with impaired avoidance of obstacles during locomotion (Chen, Schultz, Ashton-Miller, Giordani, Alexander, & Guire, 1996), increased postural sway during quiet stance (Melzer, Benjuya, & Kaplanski, 2001), and impaired balance control following unexpected perturbations (Rankin, Wollacott, Shumway-Cook, & Brown, 2000). Although all present participants were active, functionally independent community dwellers who showed no overt symptoms of cognitive impairment, the matching paradigm used in the present study was sufficiently sensitive to detect subtle changes in attention or memory which, otherwise, might not be observed. When continuous feedback about the reference position was available during contralateral matching, elderly participants showed improved performance, suggesting that utilization of on-line proprioceptive feedback is only minimally impaired with age, at least for upper limb-position matching tasks.

As previously mentioned, declines in proprioceptive acuity may be partly due to age-related changes in cognitive function. To what extent muscular and nervous system degeneration contributes to this phenomenon is unclear. A significant reduction in the number of extrafusal muscle fibers has been shown to occur with age (Brooks & Faulkner, 1994), leading to an overall reduction in the number of muscle spindles available to code for changes in muscle length (Swash & Fox, 1972). Aging led to a reduction in the dynamic sensitivity of muscle spindles which would affect both positional and velocity feedback (Miwa, Miwa, & Kenro, 1995).

Central nervous system degeneration can be viewed as playing a significant role in age-related proprioceptive impairment. In addition to a reduction in the number of alpha motor neurons, brain areas involved in the planning of descending motor commands also undergo significant deterioration in the elderly (Cruz-Sanchez, Moral, Tolosa, de Bellerosche, & Rossi, 1998). Of particular importance is the cerebellum, which plays a critical role in updating and correcting movement via proprioceptive feedback involving spinocerebellar pathways and which may also play a role in maintaining spindle sensitivity via activation of the fusimotor system (Prochazka, 1986).

In the present study a significant reduction in upper limb proprioceptive acuity was noted for elderly individuals which, when taken together with lower limb studies, suggests that age-related proprioceptive impairment is a generalized phenomenon and not related to specific aspects of motor performance. While the mean proprioceptive error reported here for the elderly group may seem negligible (5.7°), the potential for errors during functional movement can be illustrated when one considers that a 5.7° elbow error, coupled with an average adult forearm-hand link length of approximately 44 cm (Chaffin, Andersson, & Martin, 1999), translates into a finger-tip position error of approximately 4.4 cm. This represents a significant end-point error which, for upper limb tasks, can markedly affect accuracy of reaching and manipulation tasks and may also lead to postural instability wherever the arm is used to compensate for balance disturbances. Thus, the ability to perform many functional tasks safely and successfully can be significantly compromised with proprioceptive deficits of the magnitude reported here.

Lastly, the novel matching paradigm employed in this study provided a sensitive means of assessing proprioceptive acuity under conditions which vary in task difficulty. Thus, it may be an effective method of assessing both cognitive and sensorimotor declines in older populations and those with functional upper limb impairments such as stroke, Parkinson's Disease, or neuromuscular injuries or disease.

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