Published in final edited form as:

Clin Biomech (Bristol, Avon). 2007 December ; 22(10): 1088–1095.

Asymmetrical ground impact of the hands after a trip-induced fall: experimental kinematics and kinetics

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Abstract

Background—Distal radius fractures are among the most common fall-related fractures. The manner in which the upper extremities are used for protection during a fall may exert a considerable influence on the incidence of injury. Here, we sought to determine the degree to which the assumption of sagittal plane symmetry was valid in unexpected falls after a trip, and to quantify the effects of asymmetrical upper extremity motion on impact kinematics and kinetics.

Methods—The motion of eight healthy older women who fell after being unexpectedly tripped was quantified. Impact kinematics and kinetics of 36 adults who intentionally fell onto force plates with their hands positioned either symmetrically or asymmetrically were quantified.

Findings—Just prior to safety harness engagement the wrists of the older women were not positioned or moving symmetrically relative to the midpoint between the shoulders. Asymmetry did not affect the peak reaction force magnitude, but increased the degree to which force was directed along the axis of the radius (axial component of the unit vector $k=0.949$ versus $k=0.932$, $P=0.026$). Asymmetry resulted in greater wrist dorsiflexion (47° versus 43° , $P=0.019$) compared to symmetrical trials and increased temporal offset (33ms versus 11ms, $P<0.001$) between right and left ground impacts.

Interpretation—Kinetics and kinematics arising from asymmetric impact may meaningfully affect the fracture strength of the distal radius. Because trip-induced falls in older women may result in asymmetric upper extremity impact, these differences in landing kinematics and kinetics due to asymmetry merit consideration when developing clinical interventions to prevent fall-related fractures.

Keywords

aging; biomechanics; falls; injury; wrist

Introduction

In the United States, distal radius (Colles') fractures are among the most common fall-related fractures in adults over the age of 65 years, having an annual incidence of 8–10 fractures per 1000 person-years in older women. Colles' fractures are associated with significant functional impairment, functional limitation, and disability, including diminished performance of activities of daily living, non-unions, secondary osteoarthritis, and chronic pain (Vogt et al., 2002). Distal forearm fractures are responsible for 39% of all physical therapy sessions

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attributable to osteoporotic fracture (Melton, 2003). Based on the incidence, the negative influence on quality of life, and the economic impact of Colles' fractures, it is of great interest to reduce the frequency with which these injuries occur.

In a forward-directed fall the upper extremities can protect the head and thorax from impact-related injury by diminishing or even arresting the momentum acquired by the body during the descent to the ground. However, in doing so the upper extremities must absorb potentially injurious impact loads. An impact force of 1.1 to 4.1 kN is sufficient to produce a wrist fracture (Augat et al., 1998) and both experimental and model-based studies have shown that falls from standing height can result in upper extremity forces that exceed this threshold (Chiu and Robinovitch, 1998; Kim and Ashton-Miller, 2003). The manner in which the upper extremities are used for protection during a fall may exert a considerable influence on the incidence of injury. For example, elbow extension at impact increases with the height of the fall, increases the peak impact force and, subsequently increases the likelihood of sustaining a wrist fracture (DeGoede and Ashton-Miller, 2003).

Experimental studies of how the upper extremities arrest body momentum at impact following a forward-directed fall have used motor tasks that simulate the descent phase of a fall (Chiu and Robinovitch, 1998; Chou et al., 2001; DeGoede and Ashton-Miller, 2003; DeGoede et al., 2002; Hsiao and Robinovitch, 1998; Kim and Ashton-Miller, 2003; Lo et al., 2003; Palvanen et al., 2000). These motor tasks, such as falling forward in the sagittal plane onto the hands from a kneeling position, offer control over experimental conditions and safely circumvent potentially injurious impact forces that can arise from larger falling heights. However, during these types of experiments, the unavoidable preparatory time prior to fall initiation allows subjects to pre-plan execution of the motor task. Preplanning generally exerts a positive influence on the execution of the subsequent motor task (Troy and Grabiner, 2005) and this may be particularly so for older adults (Bherer et al., 2004). In contrast, such preparatory time is reduced or absent during actual falling events. Furthermore, most motor tasks used to simulate forward falls are restricted to the sagittal plane and initially position the upper extremities in a symmetrical manner with respect to the trunk. However, frontal and transverse plane rotations during falls following an induced trip are common. In addition, because upper extremity motion during gait is reciprocal, it is possible that upper extremity impact with the ground may be asymmetrical. This raises the possibility that protocols that cannot avoid pre-planning may result in patterns of upper extremity use that are different than during actual falls.

The purpose of the present study was twofold. First, we sought to determine the extent to which hand motion is symmetrical following a forward-directed trip induced fall in older women. We hypothesized that older women would not use their arms in a symmetrical manner during the descent phase of a trip-induced fall. Second, we quantified the influence of asymmetrical ground impact on wrist kinematics and kinetics following simulated forward falls in young adults. We expected that asymmetrical ground impact would change the direction of the ground reaction force relative to the forearms and would increase the temporal offset between right and left impacts. We further hypothesized that larger temporal offsets would be associated with increased ground reaction force magnitude in the first hand to impact the ground.

Methods

Experiment 1: Hand symmetry prior to ground contact after a trip-induced fall in older women

Subjects—The data from eight healthy older women (mean age 72 SD 5 years, mean height 1.58 SD 0.6 m, mean mass 71 SD 18 kg) were selected from a larger cohort of 79 older adults for analysis in this study (Pavol et al., 2001). Subjects were selected based on the criterion of their having fallen following an induced trip.

Protocol—The institutionally reviewed and approved protocol has been previously described in detail (Pavol et al., 2001). Briefly, a six camera motion capture system (Motion Analysis, Santa Rosa, CA) operating at 60 Hz recorded the motion of 19 passive reflective markers subsequently used to create a 13-segment model of the body. The present analysis quantified data from the shoulder and wrist markers, which were placed bilaterally on the acromion processes and at the midpoint of the radial and ulnar styloid processes, respectively. Falls to the ground were prevented using an individually adjusted safety harness. Fall could occur unimpeded but, even when the subject was fully prone and supported by the harness, contact of the knees and hands with the laboratory floor was precluded. After a series of control trials and a series of trials during which the safety harness was worn in the absence of the threat of a trip, a series of trials was collected during which the subjects were aware that they might be tripped. Subjects were not aware, however, of the specific trial during which or the means by which the trip would be induced. The trip was induced by a concealed, pneumatically driven obstacle that rose 5 cm above the floor in about 150 ms. A rope, one end of which was held by an investigator, was positioned across the walkway approximately 1.5 m before the obstacle and served to mislead the subjects regarding the mechanism of the trip. A trial was classified as a “fall” if the subject was fully and continuously supported by the harness after the induced trip. All of the subjects included in this analysis fell after being tripped.

Data Analysis—Direct measurement of upper extremity symmetry at the time of ground impact was not possible because subjects were not allowed to fall completely to the laboratory floor. Therefore, a measure of symmetry was determined 0.0167 seconds prior to the instant the safety harness engaged. This measure was the difference between the positions and velocities of the wrist markers and those of the shoulder midpoint, defined as the midpoint of a line between the right and left shoulder markers. In the direction of walking (x) positive position and velocity values indicated that the wrist was positioned in front of or moving faster than the shoulder midpoint, respectively. In the frontal plane (y) positive position and velocity values indicated that the wrists were positioned laterally to or moving laterally relative to the shoulder midpoint. Wrist marker vertical position was expressed in terms of the z-axis of the laboratory coordinate system in which the floor height was 0.0 m.

The wrist markers were considered spatially asymmetrical if, across all subjects, the absolute value of the difference between right and left wrist markers was significantly greater than zero. This was tested using a one-sample t-test. All statistics were performed using SPSS (SPSS Inc., Chicago, IL).

Experiment 2: Wrist kinematics and kinetics during symmetrical and asymmetrical ground contact following a simulated fall

Subjects—The data from twenty-seven young adults (16 men, mean age 24 SD 4 years, mean mass 71 SD 14 kg) who previously participated in a symmetrical ground contact protocol (Reed-Troy et al., 2005) were analyzed. A separate group of nine adults (2 men, mean age 30 SD 10 years, mean mass 61.5 SD 9.7 kg) participated in an asymmetrical ground contact protocol. All subjects provided written informed consent prior to participating in this institutionally reviewed and approved study. In both the symmetrical and asymmetrical protocols, each subject performed a total of 12 forward falls from an upright kneeling position during which each hand contacted a different force plate (AMTI, Newton, MA). Each force plate was marked with four targets marking the corners of a 25 cm square (Figure 1a). Targets 2 and 4 were each located 28 cm from their respective pair on the opposite force plate. For comparison, the mean biacromial breadth is 36.6 cm in women and 41.1 cm in men in the United States (CDC, 1994). Prior to testing, a subject-specific position was determined from which each trial was initiated. From this position, when the subject achieved a prone position his/her nose approximated a marker placed between the force plates. Each trial consisted of

leaning forward from the upright kneeling position while keeping the trunk-thigh angle fixed and arresting the motion with their hands placed on the indicated targets. Subjects performed three trials at each of four hand contact orientations and before each trial was initiated, subjects' hands were relaxed at their sides. For the symmetrical ground contact protocol, the left and right hands were targeted to the identically numbered targets on the left and right force plates, respectively (Figure 1a). For the asymmetrical ground contact protocol, the ground contact positions of the hands were varied to achieve asymmetry vertically and horizontally with respect to the longitudinal axis of the trunk (either target 2 or 4). This resulted in four total asymmetrical target combinations (Figure 1 b and c). Three trials were performed by each subject at each combination of targets.

Data Analysis—Force plate data were collected at a sampling rate of 2400 Hz. Passively reflecting markers were placed bilaterally over the third metacarpal (80 mm distal to the wrist axis of rotation), the radial and ulnar styloid processes, the medial and lateral epicondyles, the acromion processes, the greater trochanters, and over the sacrum, the left scapula, and the forehead. Motion of the markers was recorded at 240 Hz using an 8-camera motion capture system (Motion Analysis, Santa Rosa CA). With the exception of calculations of time-related variables, each of the three trials performed at a given target were averaged to produce a single data point for that location.

The wrist flexion axis of rotation was defined as the line connecting the radial and ulnar styloid process markers, and wrist joint center was the midpoint of the axis. The elbow flexion axis of rotation was defined as the line connecting the markers placed on the medial and lateral epicondyles, and elbow joint center was the midpoint of the axis. The wrist was assumed to have zero ulnar deviation if a line from the third metacarpal marker to the wrist center was perpendicular to the wrist axis of rotation. Ulnar deviation was calculated as the offset from the perpendicular line: a positive angle indicated ulnar deviation and a negative number indicated radial deviation. Wrist dorsiflexion was the included angle between the line connecting the metacarpal marker and wrist joint center, and the line connecting the wrist joint center and the elbow joint center. (Correction for the offset of the metacarpal marker from the surface of the hand was made during this calculation). The time of hand contact with a force plate was defined as the instant at which the resultant force exceeded 5% of subject body weight (BW). The dependent kinematic variables analyzed were: wrist dorsiflexion at the instant of the peak resultant force, average wrist dorsiflexion velocity from the time of force-plate contact to the instant of peak resultant force, and ulnar deviation at the instant of the peak resultant force.

For each arm, a local coordinate system was defined with the z-axis directed along the forearm (wrist center to elbow center), the x-axis directed laterally along the axis of wrist flexion (wrist center to ulnar styloid process marker), and the y-axis directed dorsally from the wrist center. Resultant ground reaction forces, expressed as a percentage of the body weight, were described by the magnitude and a unit vector $[i, j, k]$ representing [lateral, dorsal, axial] components and referenced to each arm's coordinate system. Individual resultant forces were calculated at the instant of peak force based on the assumption that the likelihood of fracture is maximal at this time. The dependent kinetic variables analyzed were: peak force magnitude, and the vector components i , j , and k .

Statistics—To determine whether asymmetric ground impact affected wrist kinematics and kinetics, we examined the extent to which the three-trial-average of each variable changed as a result of the hands being in a symmetrical position versus an asymmetrical position. Although the subject populations from the symmetrical and asymmetrical groups were not ideally matched, no significant effect of gender was observed and all ground reaction forces were expressed as a percent of body mass, thus removing its influence. In one set of comparisons

we examined the difference in each variable between its symmetrical value with both hands at target #4 and the asymmetrical values in which the non-dominant hand was placed on target #2 or target #3 (Figure 1b). In a second set of comparisons we examined the difference in each variable between its symmetrical value with both hands at target #2 and the asymmetrical values in which the non-dominant hand was placed on target #1 or target #4 (Figure 1c). In each case, we used independent-sample t-tests to determine how the non-dominant (moved) hand was affected by the change in target location, and to examine how the dominant (unmoved) hand was affected by the change in configuration. Additionally, the general effect of symmetry was examined by comparing the symmetrical and asymmetrical data for each variable using a data set that consisted of all 12 trials combined, regardless of target location, using an independent samples t-test.

To examine the effect of the two protocols on temporal asymmetry, the absolute time offset between right and left ground contact was calculated as $|\text{left impact time} - \text{right impact time}|$. The absolute time offsets from the symmetrical and asymmetrical ground contact protocols were compared using independent t-tests. Each individual trial, rather than the average of three trials, was considered for this calculation. To test the hypothesis that large temporal offsets would be associated with larger ground reaction forces, Pearson's correlation coefficients were calculated for temporal offset versus ground reaction force magnitude for each hand in each trial.

Results

Experiment 1

Just prior to the instant at which the safety harness was engaged the wrist marker positions and velocities were asymmetric relative to the midpoint of the line between the right and left shoulder markers (Table 1). The absolute difference between the right and left wrist positions and velocities in the direction of walking (x), mediolateral (y), and vertical (z) directions were significantly different than zero ($P < 0.05$). The difference between the resultant velocity of the right and left wrist markers, 59 cm/s, (SD: 46 cm/s) was also significantly different than zero ($P = 0.008$, Figure 2).

Experiment 2

In general, the symmetrical and asymmetrical impacts resulted in similar loading magnitudes. The peak resultant forces for all trials and both hands in the symmetrical and asymmetrical protocols were 92 (SD 38)% BW and 94 (SD 30)% BW, respectively ($P = 0.56$). The peak resultant forces for the symmetrical and asymmetrical protocols were achieved 28 (SD 10) ms and 25 (SD 9) ms after contact with the force plate, respectively ($P < 0.001$). Asymmetrical trials generally increased wrist dorsiflexion (47° (SD 11°) versus 43° (SD 6°), $P = 0.019$), caused forces to shift from medial to lateral (asymmetrical $i = 0.030$ (SD 0.124) versus symmetrical $i = -0.051$ (SD 0.143), $P = 0.001$), and resulted in more axially directed forces ($k = 0.949$ (SD 0.039) versus $k = 0.932$ (SD 0.049), $P = 0.026$) compared to symmetrical trials. Figure 3 and Table 2 summarize the nonsystematic kinematic and kinetic changes that occurred in symmetrical compared to asymmetrical positions.

Even in symmetrical configurations, the hands did not always experience symmetrical loads (Table 2). In each of the four symmetrical targets, subjects loaded their right wrists significantly more laterally than their left wrists ($p = 0.013$). The medial/lateral force component (i) was the only component affected by target location. At symmetrical targets 1 and 2 the reaction force was, on average, directed laterally ($i = 0.176$ and $i = 0.064$ respectively), whereas in symmetrical targets 3 and 4 the force was directed medially ($i = -0.043$ and $i = -0.165$ respectively). All

symmetrical targets' medial/lateral components were significantly different from each other ($P<0.05$) except for target 3.

Asymmetry caused the elapsed time between consecutive hand impacts to increase by a factor of three. The between-hand difference in impact time for the symmetrical and asymmetrical protocols was 11 (SD 12) ms and 33 (SD 25) ms, respectively ($P<0.001$). Larger temporal offsets were associated with resultant ground reaction forces being directed more axially (larger k component of the direction vector relative to the forearm) in the first hand to contact the ground ($r=0.441$ $P<0.001$ for right hand contact first, $r=0.351$ $P<0.001$ for left hand contact first), however peak ground reaction force magnitude in either hand was not significantly correlated with temporal offset ($P=0.427$).

Discussion

The results from these experiments suggest that older women may not use their upper extremities in a symmetrical manner during the descent phase of a trip-induced fall, and that this asymmetry may result in important kinematic and kinetic changes during wrist impact. The observed differences between wrist position and velocity just prior to the safety harness becoming engaged in Experiment 1 are suggestive of the possibility that, if the fall had been allowed to continue, ground impact with the hands may have occurred with spatial asymmetry relative to the longitudinal axis of the body (Figures 3 and 4). The data from Experiment 2 suggest that temporal offsets of 33 ms and spatial offsets of 25 cm in the x and/or y directions may significantly influence the direction, but not the magnitude, of the reaction force. This is consistent with published data in which subjects intentionally caused their hands to contact the ground at different times (DeGoede and Ashton-Miller, 2002). In a more extreme case, however, large temporal offsets could effectively change a two-handed landing into a one-handed landing, substantially increasing the amount of energy that must be dissipated by a single limb. The effect that the observed differences in impact biomechanics may exert on wrist fracture potential has not yet been explicitly addressed in the literature. However, evidence suggests that changes in loading direction have a much larger effect on fracture load of the distal radius than do clinically relevant changes in bone mineral density. When the experimental load vectors reported here were used as boundary conditions for a finite element model of the radius, its fracture strength was reduced by nearly 50% compared to when axial loads were applied (Troy and Grabiner, 2007).

Asymmetrical hand positioning may actually be advantageous by generally causing more axially-directed radius loads in the first hand to impact the ground. This may be a result of active modulation of upper extremity stiffness and positioning relative to the trunk. Additional energy absorption may be accomplished by "rolling" from one hand to the next during a temporally or spatially asymmetrical landing. Rolling may also explain why larger temporal offsets were not associated with increased ground reaction forces in the present data set. Others have suggested that the peak force magnitude is primarily dependent on deceleration of the forearm, rather than the total amount of energy delivered to the forearm (DeGoede and Ashton-Miller, 2002). Because accidental falls appear to frequently result in asymmetrical landings, it is possible that subjects are more skilled at minimizing injury risk during more natural asymmetrical impacts than during artificially symmetrical impacts.

Because of the potential for injury arising from impact forces, realistic simulation of falls in a laboratory environment can be challenging. Surrogate falling tasks reduce the risk of injury to acceptable levels but may also differ in a number of ways from falls typical of those that occur in the community. The availability of preparatory time in some experimental protocols may amplify the symmetry of upper extremity motions during the descent phase, which in turn may influence the symmetry of ground contact and the subsequent reaction forces. We sought to

eliminate this effect by quantifying upper extremity motion of older women who fell after an unexpected trip. Additionally, we collected ground reaction forces on young adults in both symmetrical and asymmetrical surrogate falls. Although young adults differ in their physical performance from older adults, we expect that older adults would exhibit similar differences and similarities between these conditions. Asymmetrical landings appear to result in more axially directed forces and result in larger wrist dorsiflexion and ulnar deviation angles. These kinematic differences may significantly influence the manner in which the radius is loaded.

A necessary limitation in Experiment 1 was the need to avoid upper extremity-ground impact during the terminal phase of the fall. Thus, the positions and velocities of the hands at ground contact are not known nor can they likely be determined experimentally, especially in older adults. Ultimately, ground contact information is important, not only for estimation of loads experienced by the upper extremities but for realistically estimating the physiological thresholds for muscle strength, power and neuromuscular coordination required to prevent buckling of the upper extremities at impact. Therefore, further development of safe, yet realistic experimental protocols and/or mathematical models may represent the only viable avenues to advance knowledge in this area.

The data set provides novel information about upper extremity motion in older women who fell after being tripped while walking. Because these falls were a result of unexpected trips induced during locomotion, the constraints associated with other protocols that simulate upper extremity use to arrest falls were diminished. Despite foreknowledge by the subjects that the safety harness would safely and comfortably prevent a fall, the benefits to recovery task performance of pre-planning were likely considerably reduced by the ambiguity of how and when the trip would be induced. Indeed, we believe that most of the subjects probably prepared for a foot being caught by the decoy rope, rather than a forward trip of the type that was induced. Nevertheless, if the recovery task had been pre-planned, open questions include the extent to which upper extremity use is included in such an internal model, and, importantly, if so whether upper extremity use would have been similar to that reported in other simulated laboratory falls.

In conclusion, at the time after an induced forward-directed trip from which recovery was not possible and ground contact would have been imminent if not for the presence of the safety harness, the right and left wrists of the older women were positioned asymmetrically and were moving with disparate velocity. Furthermore, asymmetrical hand positioning at impact results in greater wrist dorsiflexion and ulnar deviation, larger temporal offsets, and more axially-directed ground reaction forces in young adults. However, the degree of asymmetry imposed in this study does not appear to influence the magnitude of the ground reaction forces on the wrist. Our results suggest that arm asymmetry may be protective in the sense that it reduces off-axis loading, which has been linked to decreased fracture strength. Given that peak ground reaction force magnitude may depend on the degree to which an individual “rolls” from one hand to the next and the degree to which the forearm must decelerate upon impact, focusing on reducing off-axis and total force magnitude through these two mechanisms may contribute to future improvements in fall-arrest strategies and eventually, to a reduced rate of fall-related upper extremity injury in older adults.

Acknowledgements

The authors would like to thank Tammy Owings and Michael Pavol for their prominent contributions in data collection. Funding provided by National Institute of Aging, R01AG10557 (MDG) and F32AG025619 (KLT)

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Figure 1.

Experimental setup showing the locations of the four targets; when subjects lay prone their nose touched the floor directly between the target 2 locations. In the symmetrical falls (a) each hand targeted the same target number. In asymmetrical falls, the non-dominant hand was moved from either target 4 (b) or 2 (c) to another position and the dominant hand remained at its original location (target 4 or 2, respectively).

Figure 2.

Two typical subjects whose arms are moving asymmetrically immediately prior to harness engagement. Subject video (left) compared with a three-dimensional view showing wrist, shoulder, sacral, knee, and ankle marker locations, and wrist and midshoulder velocities (vectors). Velocity vectors are at 1/3 scale relative to the axis labels and wrist velocities are taken relative to the shoulder midpoint.

Figure 3.

A summary of the changes in kinematics and kinetics when a hand is moved from a symmetrical position to an asymmetrical one.

Figure 4. Frontal plane reflective marker positions and wrist velocity vectors, relative to the shoulder midpoint, immediately prior to harness engagement.

Table 1

Mean (SD) wrist and shoulder positions and velocities at the end of data capture. Shoulder midpoint values and all *z* values are referenced to the laboratory coordinate system. Wrist *x* and *y* values reported are taken relative to the shoulder midpoint so that a + *x* indicates the wrists are positioned anterior to the shoulders, and a + *x* velocity indicates that the hands are moving faster than the shoulders in the direction of walking. + *y* indicates greater lateral distance from the midline and a + *y* velocity indicates that the hands are moving laterally; a - *y* value indicates that the wrist has crossed the midline (location) or is moving towards the midline (velocity)

	End of data capture location (m)			End of data capture velocity (m/s)		
	<i>x</i>	<i>y</i>	<i>z</i>	<i>x</i>	<i>y</i>	<i>z</i>
Shoulder midpoint	1.81(0.23)	0.92(0.15)	1.02(0.10)	2.06(0.31)	-0.08(0.28)	-0.52(0.46)
Right wrist	-0.08(0.17)	0.31(0.09)	0.64(0.11)	0.69(1.20)	-0.28(0.52)	-1.02(0.68)
Left wrist	0.15(0.20)	0.27(0.11)	0.62(0.13)	-0.43(0.73)	0.00(0.76)	-1.08(1.07)
ABS(Left - Right wrists)	0.35(0.14)	0.06(0.04)	0.07(0.08)	1.57(1.39)	0.79(0.72)	0.55(0.61)

Table 2

Mean (SD) wrist kinetic and kinematic data for symmetrical and asymmetrical positions. Significant p-values are for comparisons between a hand's asymmetrical value versus that hand's original symmetrical value. Significant p-values in symmetric cells indicate a difference between right and left hands. The unit vector components [*i*, *j*, *k*] are positive in the [lateral, dorsal, wrist-to-elbow] direction. All kinematic units are in degrees except for dorsiflexion velocity (degrees/second)

	Target 4 Symmetric		Move 4-->2		Move 4-->3	
	Left	Right	moved hand	unmoved hand	moved hand	unmoved hand
<i>i</i>	-0.188 (.078)	-0.142 (.087)*	0.042 (.104)*	-0.001 (.113)*	0.090 (.121)*	0.133 (.096)*
<i>j</i>	0.280 (.106)	0.190 (.118)*	0.214 (.098)	0.161 (.125)	0.347 (.130)	0.284 (.109)*
<i>k</i>	0.932 (.041)	0.960 (.035)	0.966 (.023)	0.974 (.027)	0.917 (.053)	0.938 (.047)
ulnar dev.	7 (5)	5 (4)	5 (7)	-1 (5)*	6 (8)	2 (6)
dorsiflexion	47 (6)	41 (6)	42 (11)	58 (9)*	48 (10)	53 (10)*
flex. velocity	255 (65)	265 (87)	278 (129)	339 (105)§	259 (103)	300 (104)
	Target 2 Symmetric		Move 2-->1		Move 2-->4	
	Left	Right	moved hand	unmoved hand	moved hand	unmoved hand
<i>i</i>	0.046 (.078)	0.082 (.098)*	0.029 (.092)	-0.115 (.066)*	-0.001 (.113)§	0.042 (.104)
<i>j</i>	0.284 (.071)	0.267 (.089)	0.313 (.076)	0.241 (.102)	0.161 (.125)*	0.214 (.098)§
<i>k</i>	0.952 (.022)	0.951 (.027)	0.942 (.026)	0.956 (.029)	0.974 (.027)*	0.966 (.023)
ulnar dev.	5 (3)	5 (5)	6 (7)	5 (7)	-1 (5)*	3 (6)
dorsiflexion	41 (6)	42 (6)	36 (7)	42 (11)	58 (9)*	45 (8)
flex. velocity	265 (81)	271 (81)	247 (71)	278 (129)	339 (105)	315 (82)

* $P < 0.05$

§ $0.05 < p < 0.07$