

Elbow joint variability for different hand positions of the round off in gymnastics

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## **Abstract**

The aim of the present study was to conduct within-gymnast analyses of biological movement variability in impact forces, elbow joint kinematics and kinetics of expert gymnasts in the execution of the Round-off with different hand positions. Six international level female gymnasts performed 10 trials of the round-off from a hurdle step to a back-handspring using two hand positions: parallel and T-shape. Two force plates were used to determine ground reaction forces. Eight infrared cameras were employed to collect the kinematic data automatically. Within gymnast variability was calculated using biological coefficient of variation (BCV) discretely for ground reaction force, kinematic and kinetic measures. Variability of the continuous data was quantified using coefficient of multiple correlations (CMC). Group BCV and CMC were calculated and T-test with effect size statistics determined differences between the variability of the two techniques examined in this study. The major observation was a higher level of biological variability in the elbow joint abduction angle and adduction moment of force in the T-shaped hand position. This finding may lead to a reduced repetitive abduction stress and thus protect the elbow joint from overload. Knowledge of the differences in biological variability can inform clinicians and practitioners with effective skill selection.

## **Highlights**

- Change in technique results in change in movement variability
- Increased variability in elbow joint abd/adduction in the T shaped technique
- Lower repeatability for internal/external rotation angles suggests specific motor strategies

## **Keywords**

Biomechanics, Fundamental, Skill, Technique, Variability, Tumbling

## **1 Introduction**

Research based evidence has shown that movement variability plays an important role in many sport skills including running (Queen, Gross, & Liu, 2006), sprinting (Salo & Grimshaw, 1998; Bradshaw, Maulder, & Keogh, 2007), athletic jumping (Wilson, Simpson, van Emmerik, & Hamill, 2008), baseball pitching (Fleisig, Chu, Weber, & Andrews, 2009) and gymnastics (Irwin & Kerwin, 2007; Gittoes, Irwin, Mullineaux, & Kerwin, 2011). Biological variability is an established component of human motor performance, as such, when a performer replicates the same movement, even when the goal remains constant, the exhibited kinematics and kinetics will vary between trials (Miller, Chang, Baird, van Emmerik, & Hamill, 2010; Preatoni, Hamill, Harrison, Hayes, van Emmerik, Wilson, & Rodano, 2013).

The traditional motor learning perspective suggests that a reduction in movement variability will aid in the development of a skilled performance (Wilson et al., 2008). From a dynamical systems perspective high movement variability in the localized joint and segmental movement strategies are beneficial to the task outcomes (Newell, 1986; Gittoes et al., 2011), and has been considered to be an essential element to normal, healthy function, thus offering flexibility in adapting to perturbations (Hamill, van Emmerik, Heiderscheit, & Li, 1999). From an injury perspective movement variability is a positive feature because it helps minimize chronic injury potential (Heiderscheit, Hamill, & van Emmerik, 2002). It is postulated that movement variability during running attenuates impact shocks when runners are subjected to large forces and demonstrates a potential relationship between variability and overuse injury (Hamill et al., 1999; Heiderscheit et al., 2002). These authors suggested that movement variability might provide a broader distribution of stresses among different tissues, potentially reducing the cumulative load on internal structures of the body. Wilson et al. (2008) observed a U-shape relationship between movement variability and skill level whilst examining intermediate and expert triple jumpers, whereby in the final stages of developing a skill, variability is accessed that brings flexibility to the system allowing it to cope with perturbations (Wilson et al., 2008).

In gymnastics, when the same skill is performed a number of times it may be expected that gymnasts are attempting to use the same technique (Hiley, Zuevsky, & Yeadon, 2013). However, movement variability occurs when the same action is repeated and even the elite athlete is not able to perform identical motor patterns (Preatoni, Ferrario, Dona, Hamill, & Rodano, 2010). Gittoes et al. (2011) investigated movement variability in whole-body and multi-

joint kinematic control strategies of expert gymnasts in the execution of fundamental backward rotating dismount skills from balance beam. The authors suggest that a self-selected multi-joint kinematic strategy is used in the impact phase for customization of the joint loading adjustments in executing the fundamental dismount skills. Hiley et al. (2013) investigated movement variability in the important aspects of high bar swinging technique. They found that the more elite gymnasts have less variability in the more mechanically important aspects of technique (e.g., the instants of maximum hip and shoulder extension and flexion as the gymnast passed through the lower part of the longswing), and more variability in some of the less mechanically important aspects. These studies are focused on movement variability of whole body coordinated movements. However, there is a lack of evidence relating to movement variability of weight-bearing limb kinematics and kinetics during fundamental gymnastics skills.

Daly, Rich, Klein and Bass (1999) demonstrated that gymnastics' training can be associated with on average more than 100 impacts per training session on the upper extremities. Weight-bearing impacts onto the hands and the repetitive compressive forces can lead to both acute and chronic injuries to the upper extremities (Davidson, Mahar, Chalmers, & Wilson, 2005). Lindner and Caine (1990) identified the floor exercise as the most hazardous gymnastics event and most injuries happened with skills that are basic or moderately difficult and well-established. In artistic gymnastics the round-off (RO) (Figure 1a) is a fundamental gymnastics skill and a key movement in the development of elite female gymnasts, owing to its association with learning more complex skills (Farana, Jandacka, Uchytel, Zahradnik, & Irwin, 2014). Two common techniques are used to perform the RO, the parallel hand position (Figure 1b) and the T-shape hand position (Figure 1c).

Farana et al. (2014) observed that different hand positions during RO in female gymnastics significantly influenced elbow loading during the second contact hand. These authors stated that the T-shape position of the hands reduces peak vertical, anterior–posterior, and resultant contact forces and has a decreased loading rates and internal adduction moment of force indicating a safer technique for the round-off. Evidence from previous research has identified that chronic elbow injuries typically stem from abduction load (Jackson, Silvino, & Reiman, 1989; Chan, Aldridge, Maffulli, & Davies, 1991; Koh, Grabiner, & Weiker, 1992; Hume, Reid, & Edwards, 2006). Furthermore, the abduction angle of the elbow produces abduction loading and probably contributes to some of the overuse injury patterns such as valgus extension overload

(Magra, Caine, & Maffulli, 2007). Common elbow injuries in gymnasts are traction injuries to the medial elbow structures such as medial collateral ligament strains, and medial epicondyle traction injuries, and compressive injuries to the posterior and lateral structures such as osteochondritis dissecans of the capitellum (Frostick, Mohammad, & Ritchie, 1999).

Different methods have been used for estimating movement variability within kinematic and kinetic parameters. Coefficient of variation (CV) and biological coefficient of variation (BCV) are common methods used to observe movement variability of key discrete variables (Queen et al., 2006; Bradshaw et al. 2008; Damm, Low, Richardson, Clarke, Carré, & Dixon, 2013). However, the use of discrete variables in the analysis of movement variability may not provide a comprehensive explanation of the observed movement, and thus many potentially informative data may be ignored (Ryan, Harrison, & Hayes, 2006). The shape of kinetic/kinematic curves is often a good indicator of how a movement task is accomplished and may help coaches/clinicians in identifying athletes'/patients' performance characteristics (Chappell, Yu, Kirkendall, & Garrett, 2002; Williams, Irwin, Kerwin, & Newell, 2012). An established method for the measurement of waveform similarity and variability is coefficient of multiple correlations (CMC) which has been successfully employed across of range of human activities (Kadaba, Ramakrishnan, Wootten, Gainey, Gorton, & Cochran, 1989; Queen et al., 2006; Ford, Myer, & Hewett, 2007; Ferrari, Cutti, & Cappello, 2010).

The aim of the present study was to conduct within-gymnast analyses to develop understanding of the movement variability in impact forces, elbow joint kinematics and kinetics of expert gymnasts in the execution of the RO with different hand position. The current study will provide useful insights into technique selection that will help coaches, athletes and clinicians. Examination of the movement variability associated with RO skill has the potential to enhance insight into the control strategy modulation demanded for effective skill development in a commonly performed gymnastic task and to further contribute to understanding of the role of movement variability in performance development and injury prevention. The relevance of this research from the coaches' perspective is to make technique selection more objective, and from a clinical perspective identify potential risk factors.

## **2 Methods**

### *2.1 Participants and Protocol*

Six international level female gymnasts from the Czech Republic were recruited as participants (age  $21.0 \pm 1.9$  years, height  $162.0 \pm 4.4$  cm, and mass  $55.8 \pm 5.1$  kg). All gymnasts were injury free at the time of testing. From these six gymnasts three of them preferred RO with parallel hand position, and three of them preferred RO with T-shape hand position. One week prior to testing gymnasts were asked to practice both techniques as part of their training session. At each floor training session, gymnasts were asked to practice 10 repetitions of the skill sequence round-off to back-handspring (FIG, 2013) with parallel hand position and 10 repetitions with T-shape position. Moreover, due to nature of RO skill the expert gymnasts had no problems during testing to change technique which were performed in random order. Informed consent was obtained in accordance with the guidelines of the Institute's Ethics and Research Committee. The research was conducted in the Biomechanical Laboratory of Human Motion Diagnostic Centre. The gymnasts completed their self-selected warm up and completed a number of practice RO trials with different hand positions. A thin gymnastic floor mat (dimension 20 mm, Baenfer, Germany) was used that was taped down onto each force plate to replicate the feel of a typical gymnastics' floor. Landing mats were used to provide safety for the gymnasts' landings. After the warm up and practice, all gymnasts performed 10 trials of RO with a parallel hand position from a hurdle step to a back-handspring, and 10 trials of RO with a T-shape hand position from a hurdle step to a back-handspring. All trials were performed with a maximal effort, in random order and separated by a one minute rest period.

**(a)**

*INSERT FIGURE 1a ABOUT HERE*

**(b)**

*INSERT FIGURE 1b ABOUT HERE*

**(c)**

*INSERT FIGURE 1c ABOUT HERE*

Figure 1. The Round-off skill (a) in female artistic gymnastics (FIG, 2013); Hand positions: (b) parallel and (c) T-shape for the round-off (reprinted from Farana et al., 2014).

## *2.2 Data collection*

Two force plates (Kistler, 9286 AA, Switzerland) embedded into the floor were used to determine ground reaction force data at a sampling rate of 1235 Hz. Since the dimension of mats covering each force plate could affect kinetic calculations, depth of the transducer was set as the sum of the manufacturer depth for the specific force plate and depth of mat, this corrected the center of pressure location. A motion-capture system (Qualisys Oqus, Sweden) consisting of eight infrared cameras were employed to collect the kinematic data at a sampling rate of 247 Hz. The global coordination system was set up so that the z-axis was vertical, y-axis was in antero-posterior and the x-axis was in the medio-lateral direction. Retroreflective markers (diameter of 19 mm) were attached to the gymnasts' upper limbs and trunk as recommended for the analysis using Visual 3D (C-motion, Rockville, MD, USA). Markers were bilaterally placed on each gymnast at the following anatomical locations: the acromio-clavicular joint, shoulder, lateral epicondyle of the humerus, medial epicondyle of the humerus, radial-styloid, ulnar-styloid, head of the second metacarpal, head of the fifth metacarpal, iliac crest tubercle, and inferior-medial angle of the scapula. Markers were also placed on the seventh cervical and tenth thoracic vertebrae. Two clusters containing three markers each were also placed bilaterally on the upper arm and forearm (Figure 2). Two photocells were used to control hurdle step velocity between 3.3 – 3.7 m/s (Farana, Jandacka, & Irwin, 2013).

*INSERT FIGURE 2 ABOUT HERE*

Figure 2. Figure showing reflective markers attached to gymnast body

## *2.3 Data processing*

The data were processed using Visual 3D (C-motion, Rockville, MD, USA). The local coordinate systems were defined using a static calibration trial in the handstand position. Three dimensional elbow angles, ground reaction forces (GRF) and internal net elbow moments were determined and all analyses were focused on the contact phase of the second hand during the RO. Kinematic variables included flexion/extension, adduction/abduction and internal rotation/external rotation elbow angles with the Cardan's angle of rotation sequence XYZ. Kinetic variables included vertical (VGRF), anterior-posterior (APGRF) and resultant (RGRF) ground reaction forces. In addition, net three-dimensional internal joint moments for the elbow in

the flexion/extension, adduction/abduction and internal rotation/external rotation were quantified by the Newton-Euler inverse dynamics technique (Selbie, Hamill, & Kepple, 2014), using the segmental inertial characteristics, hand, forearm and upper arm markers positions and ground reaction forces during second hand contact time. Net internal elbow moments of force are expressed in the local coordinate system of the upper arm. The coordinate and force plate data were low-pass filtered using the fourth-order Butterworth filter with a 12 Hz and 50 Hz cut off frequency, respectively. The GRF data and moment of force data were normalized to body mass. Continuous profiles of the GRF, elbow joint angles and elbow joint moments were time-normalized to 101 points, which represents an interval from 0 to 100% of the second hand contact time.

#### *2.4 Statistical analysis*

An individual-orientated analysis strategy was employed where differences within each gymnast were quantified using a repeated trials approach. Individual gymnast means (M), standard deviations (SD), coefficients of variation (CV%), standard errors of the mean (SEM%), and biological coefficients of variation (BCV% =  $CV\% - SEM\%$ ) were calculated (Bradshaw et al., 2007). Where the BCV value was less than 10%, the variable was considered to have low variability (Queen et al., 2006). The GRF, kinematic and kinetic continuous data were quantified using coefficient of multiple correlations (CMC) with values  $>.70$  considered to have acceptable repeatability (Kadaba et al., 1989; Queen et al., 2006). CMC determined the similarity of the waveforms over the entire second hand contact phase during the RO skills. For each variable group BCV and CMC were calculated. A Shapiro-Wilk test confirmed the normality assumption for the data set, and paired t-tests were used at a significance level of 0.05. Statistical tests were performed using the SPSS Statistics version 20 Software (IBM, Chicago, IL, USA). Cohen's *d* effect sizes (ES) incorporating the pooled standard deviation were used and ES interpreted as  $<0.2$  trivial, 0.21 - 0.5 small, 0.51 - 0.8 medium and  $> 0.8$  large (Cohen, 1988).

### **3 Results**

#### *3.1 Discrete variables*

Within-gymnast variability in impact forces was typically less than 10% for peak VGRF, APGRF and RGRF for all gymnasts in both hand positions. Significant differences were found in

group mean VGRF ( $p = 0.04$ ,  $ES = 2.4$ ) movement variability between both hand positions (Figure 3).

*INSERT FIGURE 3 ABOUT HERE*

Figure 3. Group vertical ground reaction forces profiles ( $M \pm SD$ ), biological coefficient of variation score (BCV) and coefficient of multiple correlation (CMC) score of the second contact hand in parallel (top) and T-shape (bottom) hand positions

Table I highlighted within-gymnast variability in the elbow joint kinematics, which was typically less than 10% for the abduction angle for the parallel hand position compared to the T-shape hand position for each gymnast. The within-gymnast movement variability was higher for the flexion angle in the parallel than in the T-shape hand position for each gymnast. Moreover, in the parallel hand position movement variability was greater than 10 % for Gymnasts 1, 4 and 5. Within-gymnast variability for the internal rotation angle was typically less than 10 % for all gymnasts in both hand positions. As illustrated in Table I, gymnast-specific variability in the elbow joint kinetics was typically lower for the adduction moment of force in the parallel hand position compared to the T-shape hand position for each gymnast. There was a significant difference in the group mean elbow abduction angle movement variability ( $p = 0.006$ ,  $ES = 2.1$ ) between two hand positions (Table II, Figure 4). There was a no significant difference, but a large ES in the group mean elbow flexion movement variability ( $p = 0.06$ ,  $ES = 1.4$ ) existed between two hand positions (Table II). No significant differences were found in group mean internal rotation angle movement variability ( $p = 0.55$ ,  $ES = 0.3$ ) between both hand positions (Table II). Significant differences were found between the two hand positions for group mean variability in joint moments in adduction ( $p = 0.008$ ,  $ES = 2.2$ ) (Figure 5), extension ( $p = 0.006$ ,  $ES = 2.7$ ) and large ES for external rotation ( $p = 0.06$ ,  $ES = 1.3$ ) (Table II).

*INSERT TABLE I ABOUT HERE*

*INSERT TABLE II ABOUT HERE*

### 3.2 Continuous variables

CMC was used to determine the repeatability of GRF, kinematic and kinetic variables over the entire second hand contact phase during the RO. For the 6 gymnasts over the 18 key GRF, elbow joint kinematic and kinetic there were only 4 instances of low repeatability (i.e., CMC <0.7) (Table III).

The CMC values ranged for: VGRF from 0.97 to 0.99 in parallel hand position and from 0.95 to 0.99 in T-shape hand position; APGRF from 0.95 to 0.99 in parallel hand position and from 0.97 to 0.99 in T-shape hand position, and for RGRF from 0.97 to 0.99 in parallel hand position and from 0.95 to 0.99 in T-shape hand position. No significant differences, but large ES were found in group mean CMC values for VGRF ( $p = 0.14$ ,  $ES = 1.2$ ), APGRF ( $p = 0.10$ ,  $ES = 1.2$ ) and RGRF ( $p = 0.19$ ,  $ES = 1.0$ ) between both hand positions (Table IV). Elbow joint kinematics CMC values ranged from 0.66 to 0.93 in the parallel hand position and from 0.78 to 0.93 in the T-shape hand position for flexion/extension.

*INSERT FIGURE 4 ABOUT HERE*

Figure 4. Group Elbow ab/adduction angles profiles ( $M \pm SD$ ), biological coefficient of variation score (BCV) and coefficient of multiple correlation (CMC) score of the second contact hand in parallel (top) and T-shape (bottom) hand positions

Elbow joint abduction angle showed highest repeatability among the kinematic variables ranging from 0.85 to 0.94 in parallel hand position and from 0.75 to 0.92 in T-shape hand position for ad/abduction. No significant difference, but large ES were found in group mean CMC values for elbow joint abduction ( $p = 0.10$ ,  $ES = 1.0$ ) between both hand positions (Table IV). Elbow internal rotation angle demonstrated the lowest repeatability among the kinematic variables and ranged from 0.63 to 0.92 in the parallel hand position and from 0.65 to 0.93 in the T-shape hand position (Figure 5). No significant difference were found in group mean CMC values for internal rotation angle ( $p = 0.77$ ,  $ES = 0.10$ ) between both hand positions.

Elbow joint adduction moment demonstrated the highest repeatability among the kinetic variables ranging from 0.94 to 0.98 in the parallel hand position and from 0.93 to 0.97 in the T-shape hand position (Table III). Different patterns in joint moments in the ab/adduction, were found for two of the six gymnasts in the T-shape hand position. A significant difference in group

mean CMC values was found in the adduction moment of force ( $p = 0.02$ ,  $ES = 1.6$ ) between the two hand positions (Table IV, Figure 5). The CMC values for elbow joint kinetics ranged from 0.81 to 0.95 in the parallel hand position and from 0.93 to 0.97 in the T-shape hand position for the extension moment. The CMC values for the external rotation moment ranged from 0.88 to 0.94 in the parallel hand position and from 0.85 to 0.97 in the T-shape hand position. No significant difference, but large ES were found in group mean CMC values for the extension moment ( $p = 0.13$ ,  $ES = 1.3$ ) (Table IV).

*INSERT FIGURE 5 ABOUT HERE*

Figure 5. Group Elbow ab/adduction moments profiles ( $M \pm SD$ ), biological coefficient of variation score (BCV) and coefficient of multiple correlation (CMC) score of the second contact hand in parallel (top) and T-shape (bottom) hand positions

*INSERT TABLE I ABOUT HERE*

*INSERT TABLE II ABOUT HERE*

#### **4 Discussion**

Human movement biomechanics plays a vital role in understanding factors that may influence biological failure injury (Nigg & Herzog 2007; McGinnis, 2005). A contemporary dynamical systems perspective suggests movement variability plays a functional role in the performance of athletic tasks (Hamill et al., 1999; van Emmerik, Hamill, & McDermott, 2005). Understanding the nature of variability of biological systems during skilled performance can provide useful information relating to injury risk. Previous studies showed that major career ending injury site in female gymnastics is the elbow joint complex, which is susceptible to micro traumatic lesions (Jackson et al., 1989; Chan et al., 1991; Koh et al., 1992). Therefore, the current study examined the within-gymnast variability of elbow joint kinematic and kinetic measures associated with the execution of two different techniques of RO skills performed by expert female gymnasts.

Differences in VGRF suggest that there appears to be a change in movement variability between the two techniques of the skill (Figure 3). Based on the earlier work of Farana et al. (2014), which demonstrated significantly higher peak VGRF values for the parallel hand

position, it may be suggested that there is a compensation mechanism in place to accommodate for this increased force. Observations from the current study report a reduced variability in the parallel hand position, with the combined increased peak VGRF (Farana et al., 2014). This reduced variability will increase the biological load due to repeated forces. These two factors have been previously identified as potential injury mechanisms (Whiting & Zernicke, 2008). As such this observation further reinforces the use of the T-shape technique.

In the current study, higher gymnast individual variability in the elbow joint abduction angle and corresponding internal adduction moment was observed in the T-shape hand position compared with the parallel hand position for each gymnast. Moreover, individual variability in abduction angle and internal adduction moment BCV was higher than 10% during the T-shape technique for four and five out of the six gymnasts, respectively (Table I). Additionally, significant differences in the group mean elbow abduction angle BCV and internal adduction moment BCV (Figures 4 and 5) shows a significant increase in movement variability in the T-shape hand position compared to the parallel hand position (Table II). These findings indicated that during the parallel hand position the elbow joint may be exposed to repetitive abduction load due to more constant magnitude of internal adduction moment (Figure 5). Repetitive abduction load may lead to micro-trauma and chronic elbow injuries (Hume et al., 2006). More specifically, internal adduction moment may be inferred as a marker of medial collateral ligament strain (Hurd, Kaufman, & Murthy, 2011). Farana et al. (2014) stated that significantly lower peak elbow joint abduction angle and corresponding adduction moment may support the use of a T-shape hand position during RO due to reduced elbow joint complex overload and lower injury potential. Higher variability in the elbow joint movement in ab/adduction suggests a broader distribution of loads among different tissues, potentially reducing the cumulative load on internal structures of the joint (Hamill et al., 1999).

The experienced gymnasts in the current study demonstrated a reduced variability for elbow flexion angle and extension moments in the T-shape hand position (Table I). These could be explained from the performance perspective, due to the fact that elbow flexion/extension is biomechanically a key aspect to successful technique performance. This observation concurs with the findings reported by Hiley et al. (2013) who showed that in elite gymnasts there was lower variability in the mechanically important aspects of gymnastic performance. From this perspective the T-shape position may provide a more stable technique of the RO skill. Lower

within-gymnast variability was observed for internal rotation angle for both techniques (Table I). Moreover, during impact movements like RO, forearm rotation plays an important role. As forearm internally rotates during the T-shape hand position, peak abduction angle and adduction moment decrease with increase in abd/adduction movement variability (Figure 4 and 5). These findings indicated that the change in technique of the same motor task may result in reducing abd/adduction movement variability. Discrete measures of variability allows the quantification of movement variability in a way that does not rely on a large sample size, and provides information which is easy to interpret and understand by the athlete or coach (Preatoni et al., 2013). On the other hand, it has been recognized that, sometimes, analyzing discrete variables from isolated joints does not effectively capture the complexity of the coordinated motions of components of the body (Bartlett, Wheat, & Robins, 2007).

The high CMC values for GRF curves for all gymnast shows high repeatability and thus low within-gymnast variability in both hand positions. However, large ESs indicates an increased level of variability in the T-shape hand position (Table IV). In our sample of expert gymnasts the higher within-gymnast repeatability of elbow joint kinematics and kinetics were found in ab/adduction for the parallel hand position (Table III). This may indicate repetitive abduction stress which may lead to overload and biological failure that occurs due to similar RO skill. This is further highlighted by, different patterns in joint moments in the ab/adduction, which was observed for two of the six gymnasts. These participants showed an internal abduction moment observed near the end of the second hand contact phase during the RO in T-shape hand position. Table II highlighted that expert gymnasts show the lowest repeatability through a reduced CMC score for internal/external rotation angles for both hand positions compared to movements in the other planes. Three gymnasts showed CMC scores less than 0.7, two for the parallel and one for the T-shape hand position. Transverse plane motion has previously been reported to demonstrate reduced CMC values ( $<0.7$ ), in different motor tasks including gait (Mackey, Walt, Lobb, & Stott, 2005), or landings (Ford et al., 2007). Differences in the elbow joint kinematic variability associated with each gymnast and skill technique support previous suggestions that the functionality of variability may not be generalized (Newell, van Emmerik, Lee, & Sprague, 1993; Bartlett et al., 2007), and that different motor strategies can be used to achieve the same motor task (Clark, 1995; Preatoni et al., 2013). These findings will have implications for injury and

performance, when potential risk factors may be identified and the process of technique selection may be more objective.

Limitations caused by using mats over force plates, could result in a decrease (absorption) of forces and affect inverse dynamics calculations. This absorption of force by the mat may highlight the lower initial loading rate in both hand positions (Figure 3). However, using this mat is more valid given that the gymnasts work on a floor with this type of mat, and this approach is one that has been used successfully by McNitt-Gray, Yokoi, and Millward (1994) investigated landing strategies on different surfaces. Additionally, Arampatzis, Brüggemann, and Klapsing (2002) stated that stiffness properties of a gymnastics mat have no effect on the peak magnitude of ground reaction forces transmitted to the gymnast. The current study has benefited from the use of elite level gymnasts and has a high degree of ecological validity. However the obvious limitations in samples size reduce the wider application of these results. Future research could include different performance levels, genders and stages of learning to examine other factors that may influence the occurrence of injury. In addition this study has focused on the elbow joint and future research examining in the interaction of the other joint s of the may provide useful insights into the injury risk factors.

## **5 Conclusions**

Overall, it was found that the change in technique of the same motor task may result in changes in movement variability. The results of the current study indicated that the change techniques of the same motor task may result in reducing abd/adduction movement variability. Specifically, expert gymnasts displayed higher movement variability in the elbow joint peak abduction angle and adduction moment during the T-shaped hand position compared with parallel hand position whilst performing the fundamental RO skill. This may potentially lead to reducing abduction load and consequently protect the elbow joint from overload and biological failure due to repetitions of the same motor tasks. In the elbow flexion/extension, however, lower variability was observed for elbow flexion angle and extension moments, suggesting that the T-shape position provides a stable technique for the performance of the RO skill. Expert gymnasts show the lowest repeatability for internal/external rotation angles during a fundamental RO skill, indicating that the different motor strategies may be used to achieve the same motor task. The

application of these methods to a complex movement task can have implications to the examination and understanding of more simple tasks such as gait, running or landing.

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Table I. Biological coefficient of variation (%) for peak elbow joint angles (top) and moments (bottom) for 6 gymnasts performing a round-off with parallel and T-shape hand positions.

	Parallel			T-shape		
	Flexion	Abduction	Internal rot.	Flexion	Abduction	Internal rot.
<b>Angles</b>						
Gymnast 1	10.7	3.2	1.4	5.6	7.8	2.4
Gymnast 2	5.3	6.3	1.7	4.0	19.1	1.9
Gymnast 3	9.1	3.7	1.1	5.1	16.2	1.3
Gymnast 4	20.4	5.9	2.7	12.8	16.0	3.4
Gymnast 5	13.2	5.0	1.4	4.8	10.5	1.3
Gymnast 6	4.1	3.9	1.9	3.9	6.8	1.4
	Extension	Adduction	External rot.	Extension	Adduction	External rot.
<b>Moments</b>						
Gymnast 1	12.6	7.1	11.2	5.6	7.8	4.5
Gymnast 2	9.0	7.8	30.5	4.0	25.1	7.6
Gymnast 3	14.8	9.5	25.0	5.1	21.3	9.6
Gymnast 4	14.1	5.9	11.7	12.8	27.6	5.2
Gymnast 5	10.2	3.1	7.1	4.8	13.3	10.1
Gymnast 6	6.8	3.4	12.5	3.9	15.5	7.5

BCV < 10% = low variability

Table II. Variability for discrete variables in ground reaction forces, elbow kinematics and kinetics parameters ( $M \pm SD$ ) during the round-off for 6 gymnasts performing a round-off with parallel and T-shape hand positions.

Variable	Parallel	T-Shape	ES	p-values
<b>Biological coefficient of variation (%BCV)</b>				
Peak VGRF (%BCV)	3.1 ± 0.5	4.3 ± 0.5	<b>2.4</b>	<b>0.04*</b>
Peak APGRF (%BCV)	5.4 ± 2.4	4.9 ± 2.9	0.2	0.81
Peak RGRF (%BCV)	3.5 ± 0.7	3.9 ± 0.1	0.8	0.32
Max. elbow flexion (%BCV)	8.5 ± 3.8	4.7 ± 0.7	<b>1.4</b>	0.06
Max. elbow abduction (%BCV)	4.7 ± 1.3	12.7 ± 5.1	<b>2.1</b>	<b>0.006*</b>
Max. elbow internal rotation (%BCV)	1.7 ± 0.5	1.9 ± 0.7	0.3	0.55
Max. elbow extension moment (%BCV)	10.7 ± 3.1	4.7 ± 0.7	<b>2.7</b>	<b>0.006*</b>
Max. elbow adduction moment (%BCV)	6.1 ± 2.5	18.4 ± 7.5	<b>2.2</b>	<b>0.008*</b>
Max. elbow external rotation moment (%BCV)	16.3 ± 9.2	7.4 ± 2.3	<b>1.3</b>	0.06

Notes: GRF, ground reaction forces; VGRF, vertical ground reaction force; APGRF, anterior-posterior ground reaction force, RGRF, resultant ground reaction force; BCV, biological coefficient of variation; ES, effect size; \*p < 0.05; Bold indicates significant differences and large effect sizes between two hand positions.

Table III. Coefficient of multiple correlations for elbow joint angles (top) and moments (bottom) for 6 gymnasts performing a round-off with parallel and T-shape hand positions.

	Parallel			T-shape		
	Flexion	Abduction	Internal rot.	Flexion	Abduction	Internal rot.
<b>Angles</b>						
Gymnast 1	0.902	0.924	0.681	0.930	0.753	0.711
Gymnast 2	0.902	0.972	0.949	0.903	0.963	0.962
Gymnast 3	0.661	0.901	0.878	0.781	0.851	0.865
Gymnast 4	0.711	0.834	0.632	0.789	0.830	0.734
Gymnast 5	0.863	0.917	0.859	0.877	0.865	0.652
Gymnast 6	0.934	0.944	0.882	0.894	0.921	0.878
	Extension	Adduction	External rot.	Extension	Adduction	External rot.
<b>Moments</b>						
Gymnast 1	0.936	0.970	0.936	0.966	0.978	0.969
Gymnast 2	0.941	0.947	0.931	0.964	0.866	0.931
Gymnast 3	0.817	0.939	0.928	0.968	0.887	0.904
Gymnast 4	0.880	0.952	0.932	0.793	0.791	0.850
Gymnast 5	0.891	0.984	0.898	0.932	0.859	0.849
Gymnast 6	0.945	0.981	0.884	0.949	0.926	0.949

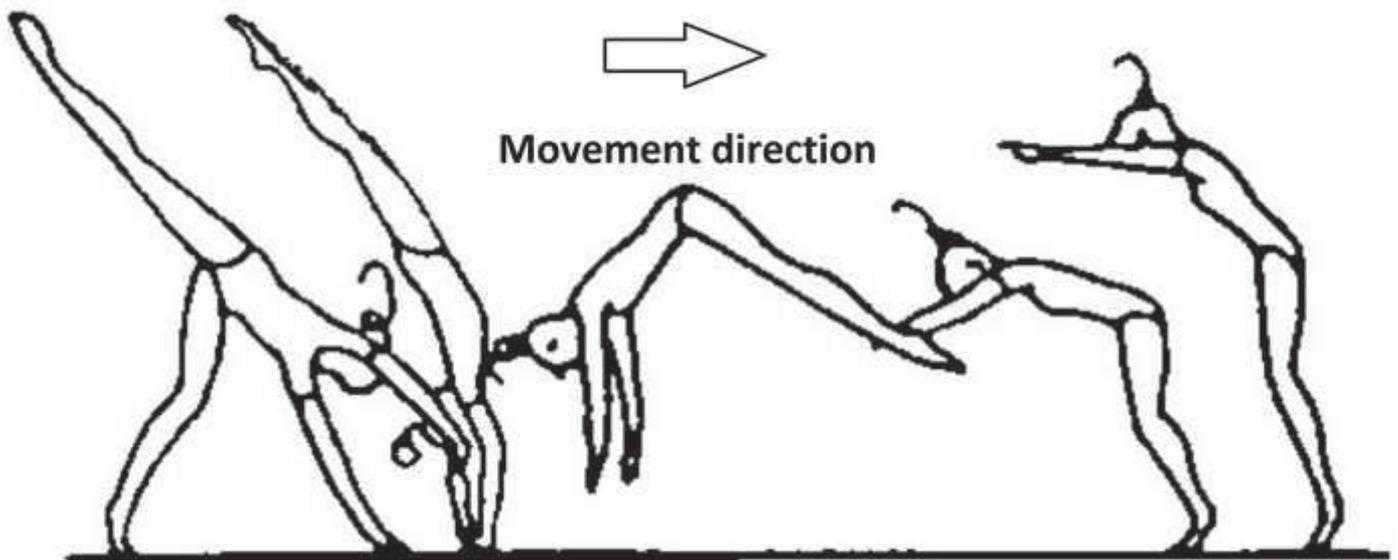
CMC > .70 acceptable repeatability

Table IV. Variability for continuous variables in ground reaction forces, elbow kinematics and kinetics parameters ( $M \pm SD$ ) during the round-off for 6 gymnasts performing a round-off with parallel and T-shape hand positions.

Variable	Parallel	T-Shape	ES	p-values
<b>Coefficient of multiple correlations (CMC)</b>				
VGRF (CMC)	0.980 ± 0.008	0.965 ± 0.015	<b>1.2</b>	0.14
APGRF (CMC)	0.982 ± 0.006	0.968 ± 0.015	<b>1.2</b>	0.10
RGRF (CMC)	0.981 ± 0.007	0.969 ± 0.016	<b>1.0</b>	0.19
Elbow flexion (CMC)	0.829 ± 0.114	0.862 ± 0.062	0.4	0.21
Elbow abduction (CMC)	0.932 ± 0.027	0.871 ± 0.080	<b>1.0</b>	0.10
Elbow internal rotation (CMC)	0.814 ± 0.126	0.800 ± 0.119	0.1	0.77
Elbow extension moment (CMC)	0.906 ± 0.054	0.956 ± 0.015	<b>1.3</b>	0.13
Elbow adduction moment (CMC)	0.962 ± 0.019	0.885 ± 0.064	<b>1.6</b>	<b>0.02*</b>
Elbow external rotation moment (CMC)	0.918 ± 0.022	0.909 ± 0.051	0.2	0.68

Notes: GRF, ground reaction forces; VGRF, vertical ground reaction force; APGRF, anterior-posterior ground reaction force, RGRF, resultant ground reaction force; CMC, coefficient of multiple correlations; ES, effect size; \*p < 0.05; Bold indicates significant differences and large effect sizes between two hand positions.

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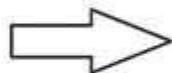


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**First contact hand**



**Second contact hand**



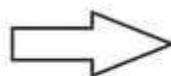
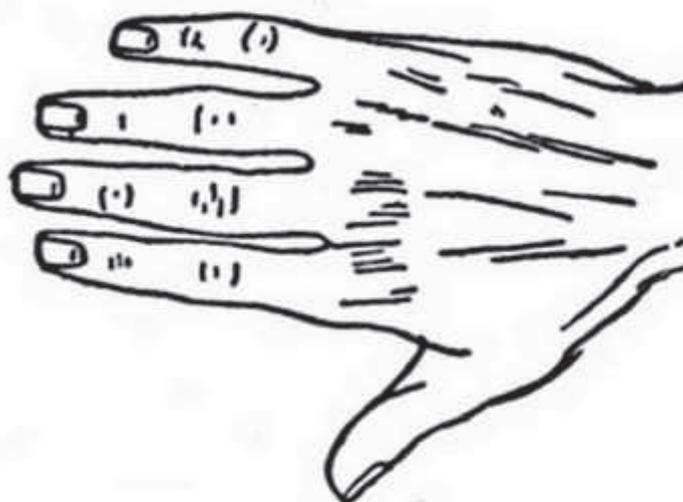
**Movement direction**

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**First contact hand**

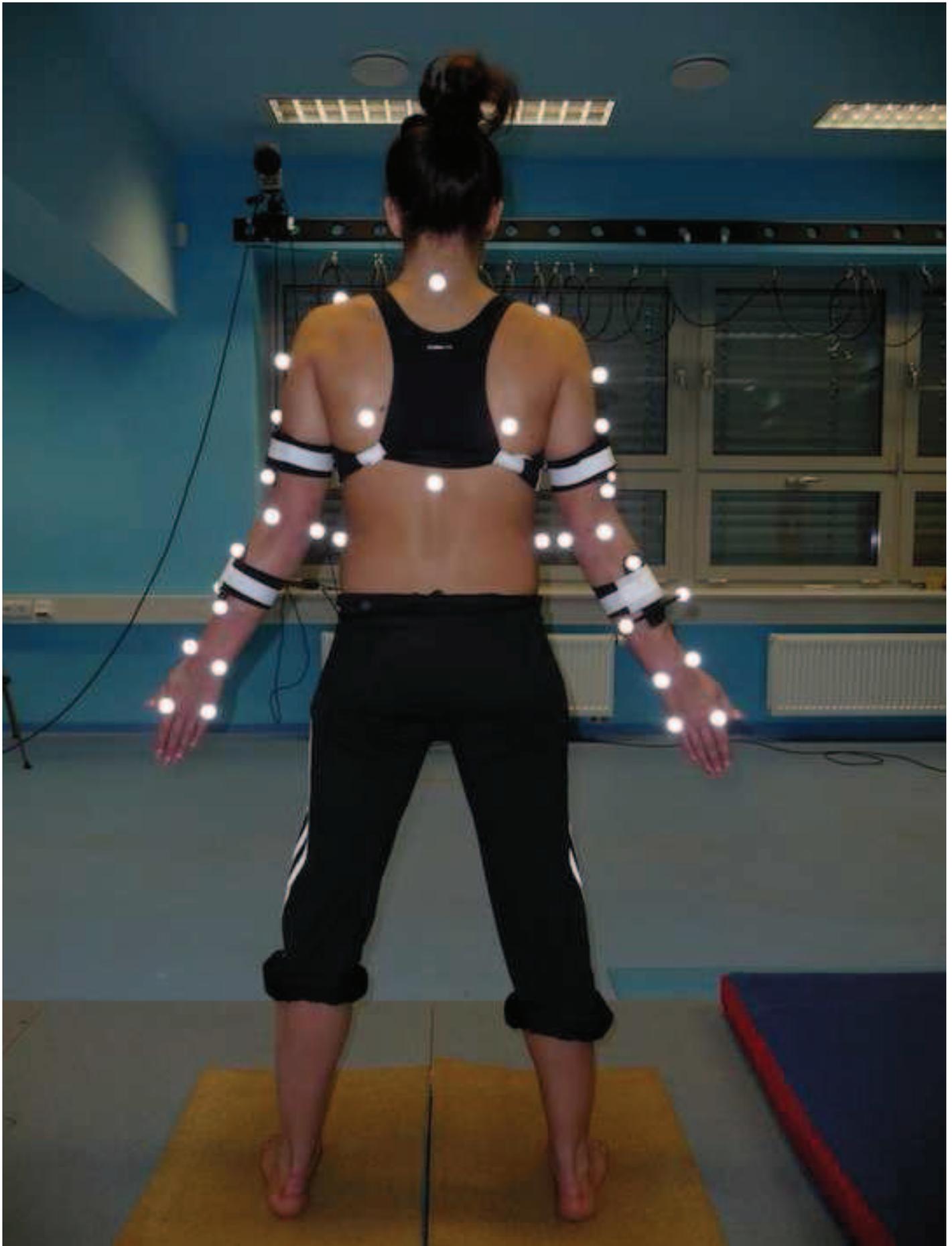


**Second contact hand**

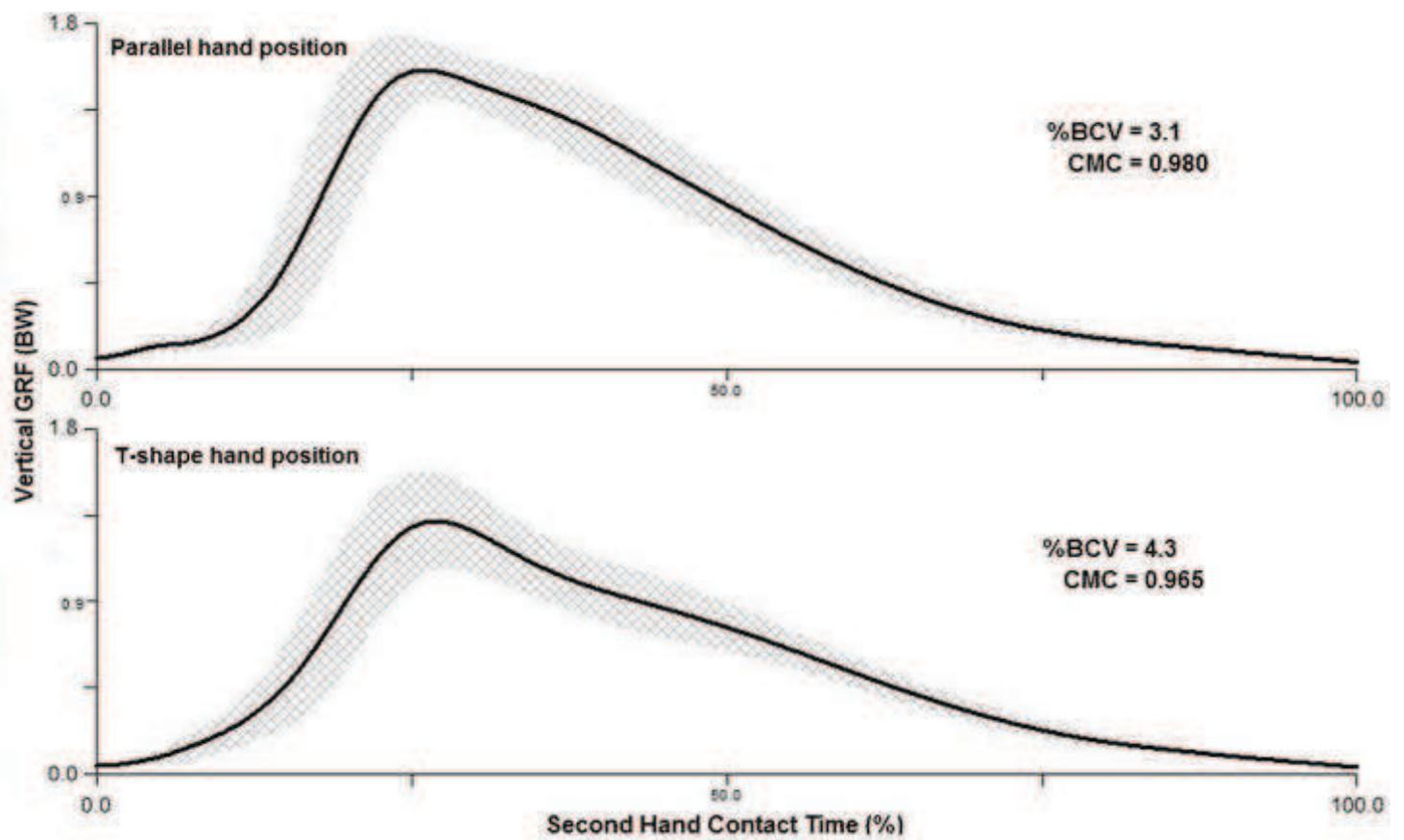


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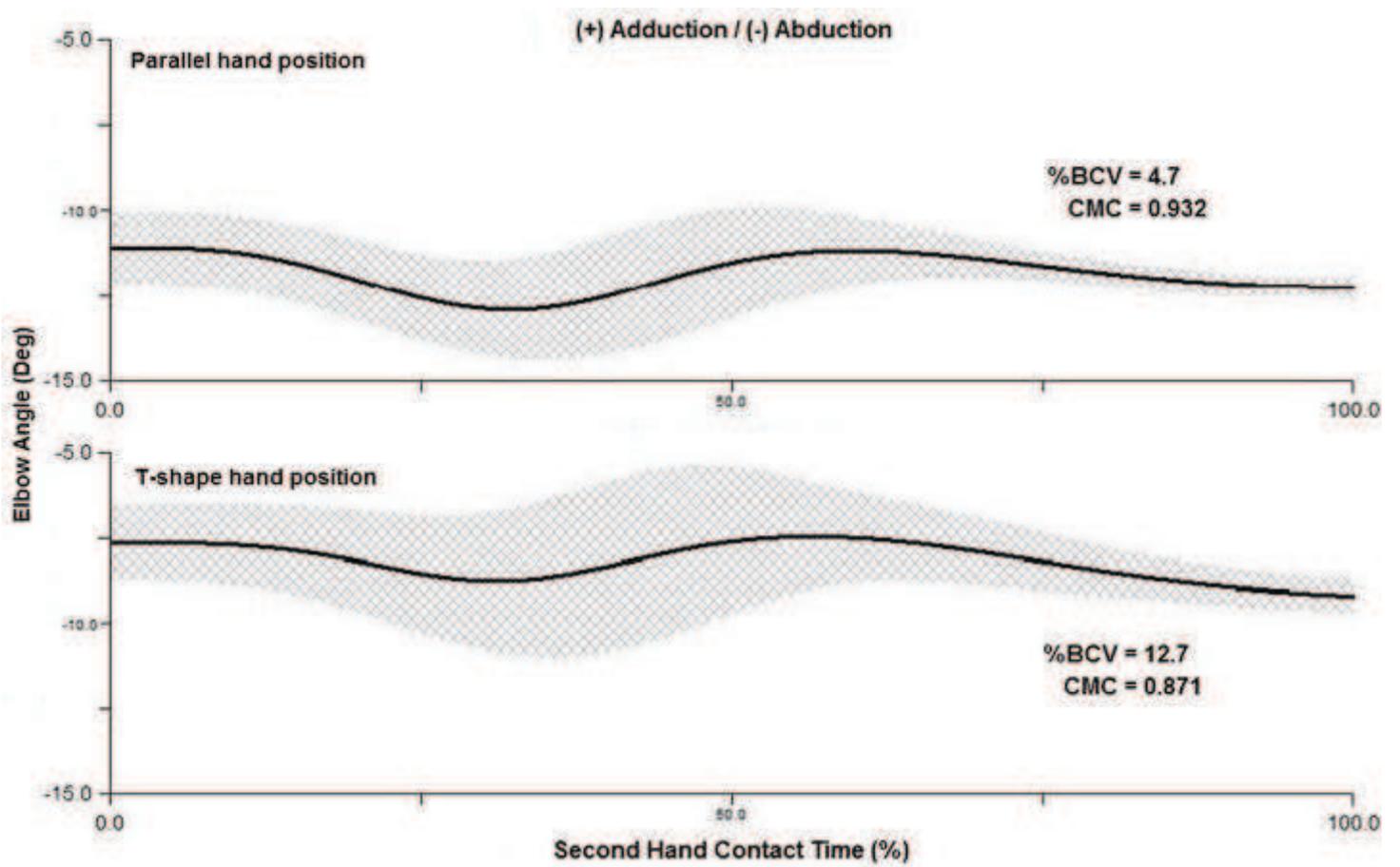
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(+) Adduction / (-) Abduction

