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Abstract

The aim of the study was to determine if sex differences exist in the key elbow and wrist joint injury risk factors during different cartwheel (CW) and round-off (RO) techniques performed by young male and female artistic gymnasts. Sixteen active young gymnasts (8 males and 8 females) performed 30 successful trials of CW and RO with three different hand positions (parallel (10), T-shape (10) and reverse (10)). Synchronised kinematic and kinetic data were collected for each trial. Two-way repeated measures ANOVA (3 × 2, technique × sex) and effect-sizes (ES) were used for statistical analysis. In conclusion, female gymnasts exhibited greater normalised peak vertical ground reaction forces (VGRF), elbow and wrist compression forces and elbow internal adduction moments during CW and RO skills compared with male gymnasts. In both sexes, the parallel and reverse techniques increased peak VGRF, elbow and wrist compression forces and the elbow internal adduction moment. Increased elbow flexion resulted in decreased peak VGRF, elbow compression forces and elbow internal adduction moment. Injury risk factors including elbow extension and internal adduction moment with axial compression force suggest that a CW and RO in reverse and parallel techniques can be hazardous especially for young female gymnasts.

Keywords: biomechanics, technique, injury & prevention, gymnastics, youth, gender.

Introduction

Biophysical loading of the elbow and wrist contributes to chronic lesions in gymnasts and presents a real concern for coaches, scientist and clinicians. Injury can have adverse effects on gymnasts given the potential risk of long-term or permanent disability (including reduced quality of life). These chronic lesions can lead to early degenerative musculoskeletal disorders, high economic cost of injury treatment, loss of gymnastics participation time, and a reduction in the gymnast's well-being (Bradshaw & Hume, 2012). A specific characteristic of gymnastics training is the alternation of support between upper and lower limbs, with the upper extremities often used for weight-bearing (DiFiori, Caine, & Malina, 2006; Webb & Rettig, 2008). Weight-bearing by upper extremities generates large impact loads that are distributed through the elbow and wrist joints (Farana, Jandacka, Uchytil, Zahradnik, & Irwin, 2014; Farana, Jandacka, Uchytil, Zahradnik, & Irwin, 2017). Previous gymnastics research has highlighted that serious chronic injuries, such as osteochondritis of the humeral capitellum (Aronen, 1985; Jackson, Silvino, & Reiman, 1989) and distal radius physeal stress fracture (DiFiori et al., 2006; Webb & Rettig, 2008) may affect the elbow and wrist joints of young gymnasts aged 10 – 14 years (Gabel, 1998; Jackson et al., 1989). Moreover, these injuries are primarily a disorder of young adolescent female athletes, typically involved in a highly repetitive activity such as gymnastics (Baker, Romeo, & Baker, 2010). The biomechanical explanation often given for these injuries is abduction (valgus) stress at ground contact accompanied with higher external ground reaction forces and greater axial compression force placed on the elbow joint (Koh, Grabiner, & Weiker, 1992), as well as higher axial compression forces placed on the wrist joint when dorsiflexed (Webb & Rettig, 2008).

In gymnastics, the forward cartwheel (CW) and the round-off (RO) are two of the most fundamental skills performed on the floor and are defined as the primary way for gymnasts to change from forward to backward-rotating movements and key skills in the safe and effective motor development of gymnasts (Sands, 1984). Due to the fact that these skills are precursors to developing more complex skills, they are repeatedly performed by recreational and competitive gymnasts and are a component of school physical education curriculums. Gymnastics training requires a high frequency of performance repetition of these fundamental skills and as previous gymnastics research has shown, this can result in serious chronic elbow and wrist joint injuries (Baker et al., 2010; Daly et al., 1999; Jackson et al., 1989; Singh et al., 2008). Previous research has highlighted the importance of technique selection in gymnastics and has shown that the selection of technique may have an impact on injury and the development of a skill (Farana et al., 2014; Farana et al., 2017; Manning, Irwin, Gittoes, & Kerwin, 2011). Previous studies (Farana et al., 2014; Farana et al., 2017) have examined injury risk and technique selection associated with the choice of hand placement in RO skills performed by elite female gymnasts and highlighted that different hand placements during the RO skill have a direct influence on the bio-physical demand placed on the performer. These authors observed that the T-shape hand position reduced peak ground reaction forces (GRF), decreased elbow joint moments (Farana et al., 2014) and axial compression force applied to the wrist joint (Farana et al., 2017) compared to a parallel hand position, indicating the T-shape was a safer technique for the RO skill.

To date, research has focused on elite and young female gymnasts performing the RO and CW skills with different hand placements and the associated injury risk (Farana et al., 2014; Farana et al., 2017; Farana, Exell, Strutzenberger & Irwin, 2018). However, the RO and CW skills are repeatedly performed by both male and female gymnasts of all abilities and gaining further knowledge about the loads and techniques employed is key for coaches, gymnasts, non-gymnasts and physical education teachers. Moreover, in younger age populations the physical abilities in terms of strength and technical accuracy may differ between male and female gymnasts (Sands, 1994; Bradshaw & LeRossignol, 2004) as male gymnasts participate in more apparatus using upper limbs for weight-bearing such as pommel horse, parallel bars and rings (FIG, 2016). Previously, Kirkendall (1985) estimated that almost 60% and 30% of the skills performed by male and female gymnasts, respectively, involve weight-bearing tasks all of which require a high degree of muscular strength and/or power for successful execution. Moreover, male and female gymnasts also differ in terms of morphology and carrying angle as reported in previous research (e.g. Arampatzis & Brüggemann, 2001; Malina et al., 2013; van Roy, Baeyens, Fauvart, Lanssiers, & Clarijs, 2005). Increasing knowledge of the sex differences in CW and RO techniques may help to decrease mechanical load by informing technique selection to be less risky for each sex, and may help the FIG in terms of aligning the male and female Code of Points (Irwin & Kerwin, 2007).

Therefore, the aim of the current study was to determine if sex differences exist in key elbow and wrist joint injury risk factors during different CW and RO hand placement techniques performed by young male and female artistic gymnasts. It was hypothesised, that (H_a) females will demonstrate greater peak vertical ground reaction force, elbow joint internal adduction moment, elbow and wrist joint axial compression forces compared to males and, (H_b) that the parallel and reverse techniques would increase upper limb injury risk factors compared with the T-shape technique in both sexes.

Methods

Participants

The experimental sample consisted of 8 females (age: 10.0 ± 0.7 years, height: 137.7 ± 5.6 cm and mass: 30.6 ± 3.1 kg) and 8 males (age: 9.7 ± 1.1 years, height: 136.7 ± 7.0 cm and mass: 30.9 ± 3.3 kg) active young gymnasts with at least four years' experience of systematic training and competitive gymnastics (Table I). All gymnasts had no previous history of upper extremity injury and were injury-free at the time of testing. Informed assent and parental consent were obtained from each gymnast and his/her legal guardian, respectively, in accordance with the guidelines of the Institute's Ethics and Research Committee.

Insert Table 1 above here

Protocol

Each gymnast completed his/her self-selected warm up and a number of practice CW and RO trials in three hand positions. To increase ecological validity, a thin gymnastics floor mat (thickness 20 mm, Baenfer, Germany) was taped down onto the force plates, detailed below, to replicate the feel and cushioning of a typical gymnastics floor (Farana et al., 2014). Additionally, landing mats were used to provide safety for the gymnasts' landings. After warm up and practice trials, the gymnasts performed 10 successful trials of the CW and RO skills from a hurdle step with parallel, T-shape and reverse hand positions (Figure 1). A successful trial was determined when 1) that gymnasts hit force plate with correct hand position, and 2) when the two expert gymnastic coaches, who are also gymnastics judges were happy with the technical execution. For comparability all gymnasts had to perform the approach in a given velocity range (2.0 – 2.5 m/s for CW and from 2.5 – 3.0 m/s for RO skills), which was controlled by timing gates (EGMedical s.r.o., Brno, Czech Republic). Based on previous research by Farana et al. (2014, 2017) time gates measured and controlled the hurdle step velocity. Due to nature of cartwheel and simple RO skills different approach velocities were used for this study. These velocities were chosen based on previous a series of pilot studies where a range of 2.0 – 2.5 m/s for CW and from 2.5 – 3.0 m/s for RO skills were identified as valid for these skills. This approach was successfully used by Farana et al. 2017. The trials were randomised by individual trials and separated by a one-minute rest period.

Insert Figure 1 Above Here

Experimental set-up

A force plate (Kistler, 9286 AA, Switzerland) embedded into the floor was used to determine ground reaction force data at a sampling rate of 1200 Hz. A motion-capture system (Oqus, Qualisys, Sweden) consisting of nine infrared cameras was employed to collect the kinematic data at a sampling rate of 240 Hz and synchronised with the force plate data. Data from the force plate and the cameras were collected simultaneously. Based on C-motion (Rockville, MD, USA) recommendations, retroreflective markers (diameter of 12 mm) and clusters were attached to the gymnasts' upper limbs and trunk. Markers were bilaterally placed on each participant at the following anatomical locations: the acromio-clavicular joint, centre of shoulder deltoid muscle, lateral epicondyle of the humerus, medial epicondyle of the humerus, radial-styloid, ulnar-styloid, head of the second metacarpal. Two clusters containing four markers each were also placed bilaterally on the upper arm (Figure 2).

Insert Figure 2 Above Here

Data analysis

Marker trajectory and force data were processed using Visual3D software (C-motion, Rockville, MD, USA). Kinematic and kinetic data were filtered using a fourth-order Butterworth low-pass filter with cut-off frequencies of 12 Hz and 50 Hz, respectively (Winter, 2009). The local coordinate systems (LCS) were defined using a standing calibration trial in the handstand position (Farana et al., 2014). The LCS for the elbow and wrist were oriented such that the y-axis pointed anteriorly, z-axis points vertically, and x-axis is perpendicular to the plane of the other two axes with its direction defined by the right-hand rule (Hamill, Selbie, & Kepple, 2014). Three-dimensional joint angles for the wrist were calculated using an XYZ Cardan rotation sequence. All angles were referenced to the coordinate systems embedded in the proximal segment (Hamill, Gruber, & Derrick, 2012). In addition, the net three-dimensional elbow joint moments and elbow and wrist joint reaction forces were quantified using the Newton–Euler inverse dynamics technique (Selbie, Hamill, & Kepple, 2014) and are expressed in the LCS of the upper arm and forearm, respectively. All analyses focused on the contact phase of the second hand during the three different CW and RO techniques. Based on previous studies (Farana et al., 2014 and 2017) key injury risk variables included peak vertical ground reaction force (VGRF), elbow joint internal adduction moment (+ adduction / – abduction), elbow and wrist joint axial compression forces, elbow joint flexion (+ flexion / – extension), and wrist joint dorsiflexion (+ plantarflexion / – dorsiflexion). Wrist joint dorsiflexion angle was determined as the angle between LCS of the hand and forearm (0° indicates full extension). The GRF data, moment of force data and joint reaction force data were normalised to each gymnasts' body mass.

Statistical analysis

Statistical tests were used to examine the effects caused by the independent variables "hand position" (parallel, T-shape, reverse) and "sex" (male, female) on the dependent variables (i.e. ground reaction forces, elbow and wrist joint kinematics and kinetics). The intra-class correlation coefficient (ICC) was applied for the assessment of the measurements' reliability (Hopkins, 2000). Mean values of the 10 trials for each gymnast in each technique were calculated for all measured variables and used in statistical analysis. A Shapiro–Wilk test confirmed the normality assumption for the data and a two-way repeated measures ANOVA (3 × 2; technique × sex) was performed. Effect sizes (ES) were calculated for the ANOVA via partial η^2 and presented as <0.01 trivial; 0.01–0.06 small; 0.06–0.14 moderate and >0.14 large (Cohen, 1992). If Mauchly's test result was statistically significant, Greenhouse–Geisser corrections were used. Post-hoc tests included Bonferroni pairwise comparisons. In order to overcome the inherent limitations of a small sample, Effect size (ES) statistics were used to assess the biological relevance of the differences between mean values. According to Cohen (1992) ESs were interpreted as trivial (*d*: <0.2), small (*d*: 0.21–0.5), moderate (*d:* 0.51–0.8), or large (*d*>0.8). Statistical tests were processed using the IBM SPSS Statistics 20 Software (IBM SPSS Inc., Chicago, IL, USA). The significance level was set to $p<0.05$.

Results

Descriptive statistics with means, standard deviations and statistical results for the three techniques, male and female gymnasts for CW and RO skills are presented in Tables 2 and 3. The values of the ICC calculated from repeated measures were in the range of 0.80–0.95 for all variables.

For CW skills, a statistically significant main effects for sex were observed for peak VGRF ($p = 0.014$, partial $\eta^2 = 0.600$), for peak elbow ($p = 0.018$, $\eta^2 = 0.575$) and wrist joint ($p = 0.020$, $\eta^2 = 0.560$) compression forces, and for peak elbow flexion ($p = 0.029$, $\eta^2 = 0.516$) (Table 2). Statistically significant main effects of technique were found for elbow joint internal adduction moment of force ($p = 0.003$, $\eta^2 = 0.720$), for peak elbow flexion ($p = 0.000$, $\eta^2 = 0.827$), and for peak wrist dorsiflexion ($p = 0.009$, $\eta^2 = 0.584$). In more detail, subsequent pairwise comparisons using ES found large ES in peak VGRF between males and females in parallel technique ($d = 1.1$), reverse technique ($d = 1.1$) and T-shape technique ($d = 1.3$) (Figure 3A). Large ESs were found in peak elbow and wrist compression forces between males and females in the parallel technique (elbow, $d = 1.2$; wrist, $d = 1.1$), reverse technique (elbow, $d = 1.1$; wrist, $d = 1.1$) and T-shape technique (elbow, $d = 1.3$; wrist, $d = 1.1$). Contrasting between cartwheel techniques for the second contact hand demonstrated that the T-shape hand position elicited statistically significantly lower peak values of internal adduction moments compared to the parallel ($p = 0.000$) and reverse ($p = 0.020$) hand position in both sexes (Figure 3B).

Large ES values were found in peak elbow flexion between males and females in the parallel technique (d = 1.3), reverse technique (d = 1.2) and T-shape technique (d = 0.8) (Figure 3C).

Insert Table 2 above here

Insert Figure 3 above here

For the RO skills, statistically significant main effects for sex were found for peak VGRF (p = 0.028, partial η^2 = 0.524), for peak elbow compression forces (p = 0.001, partial η^2 = 0.815), for peak wrist compression forces (p = 0.002, partial η^2 = 0.762), and for peak elbow flexion (p = 0.002, η^2 = 0.782). Statistically significant main effects of technique were observed for peak VGRF (p = 0.000, partial η^2 = 0.770), for peak elbow compression forces (p = 0.001, partial η^2 = 0.719), for peak wrist compression forces (p = 0.000, partial η^2 = 0.794), for peak elbow internal adduction moment of force (p = 0.000, η^2 = 0.783), for peak elbow flexion (p = 0.003, η^2 = 0.715), and for peak wrist dorsiflexion (p = 0.001, η^2 = 0.700). Interaction effects were shown for peak VGRF (p = 0.000, partial η^2 = 0.825), for peak elbow compression forces (p = 0.003, partial η^2 = 0.678), for peak wrist compression forces (p = 0.000, partial η^2 = 0.732), for peak elbow joint internal adduction moment (p = 0.004, η^2 = 0.548), and for peak elbow flexion (p = 0.003, η^2 = 0.618). Subsequent pairwise comparisons using ES showed large effects for peak VGRF between males and females in the parallel technique (d = 1.6), reverse technique (d = 1.8), and a small effect in T-shape technique (d = 0.4) (Figure 4A). Comparing RO techniques for the second contact hand demonstrated that the T shape hand position elicited statistically significant lower peak values of VGRF to the parallel (p = 0.002) and reverse (p = 0.003) hand positions in both sexes (Figure 4A). Pairwise comparisons using ES found differences in peak elbow and wrist joint compression forces between males and females in the parallel technique (elbow, d = 2.5; wrist, d = 2.2), reverse technique (elbow, d = 2.8; wrist, d = 2.9) and T-shape technique (elbow, d = 1.7; wrist, d = 1.4). Elbow and wrist joint compression forces displayed significant differences between parallel and T-shape techniques (elbow, p = 0.001; wrist, p = 0.000) and between reverse and T-shape techniques (elbow, p = 0.009; wrist, p = 0.004) in both sexes. Comparing RO techniques for the second contact hand demonstrated that the T shape hand position elicited statistically significant lower peak values of internal adduction moments compared to the parallel (p = 0.000) and reverse (p = 0.003) hand positions in both sexes. In addition, large ES values were found between males and females in the parallel (d = 1.2) and reverse (d = 1.2) hand positions (Figure 4B). ES statistics found differences in peak elbow flexion between males and females in the parallel technique (d = 1.7), reverse technique (d = 2.2) and T-shape technique (d = 1.3) (Figure 4C). Comparisons of RO techniques for the second contact hand demonstrated that the T-shape hand position elicited statistically significant higher peak elbow flexion compared to the parallel (p = 0.017) and reverse (p = 0.007) hand positions in both sexes. Significant differences were also found between parallel and reverse hand positions (p = 0.025).

Insert Table 3 above here

Insert Figure 4 above here

Discussion

Protecting young athletes from exposure to injury risk is a key aim of sports science and coaching. Increasing the understanding of upper-limb injury potential of young male and female gymnasts plays a vital role for gymnasts, coaches, clinicians and scientists. In the current study, the elbow and wrist joint loading during fundamental gymnastics skills was examined to gain insights into the risk factors associated with these gymnastics techniques. The aim of the study was to determine if sex differences existed in the key elbow and wrist joint injury risk factors during different CW and RO techniques performed by young male and female artistic gymnasts. Based on the presented findings, the two hypotheses that (H_a) females will demonstrate greater external and internal kinetics compared to males; and that (H_b) the parallel and reverse techniques would increase upper limb injury risk factors compared with the T-shape technique in both sexes were supported.

Young female gymnasts exhibited greater peak VGRF of the second contact hand during the CW and RO in all three hand positions (Figure 3A and 4A). Moreover, during RO skills with both sexes, peak VGRFs of the second contact hand was highest in the reverse technique followed by the parallel and then T-shape technique with the lowest peak VGRF (Table 3 and Figure 4A). These finding are in accordance with previous studies on elite and young female gymnasts (Farana et al., 2014; Farana et al., 2018) that highlighted that the T-shape hand position reduced peak VGRF of the second contact hand compared to other techniques of these fundamental skills. Findings from the current study indicated that young female gymnasts need to produce more force to successfully perform these fundamental skills.

Previous studies have established the role of forearm rotation on elbow joint loading during the RO in elite and young female gymnasts (Farana et al., 2014; Farana et al., 2018). Current findings show significant differences for peak internal adduction moments in the CW (Table 2, Figure 3B) and RO (Table 3, Figure 4B) for parallel and reverse hand positions compared with the T-shape hand position for both sexes. These findings are in accordance with previous research by Farana et al. (2014), identifying significantly lower magnitudes of internal adduction moment in the T-shape technique compared with parallel hand position during the RO performed by elite female gymnasts. Moreover, male gymnasts demonstrated lower peaks of internal adduction moments in all three hand positions during both skills. This could be explained through the observations at the elbow joint, where male gymnasts demonstrated significantly higher elbow flexion in both skills and across all three techniques (Tables 2 and 3, Figures 3C and 4C). Evidence from previous studies has highlighted the role that elbow flexion plays in decreasing external and elbow internal loads. Chou et al. (2001) compared the elbow loads induced in forward falls, when elbows were flexed and fully extended. These authors explained that elbow flexion provides an effective damping mechanism in forward falls, and consequently minimises the risk of upper extremity injuries, with 68% reduction in abduction load of the elbow when flexed. Results from the current study suggest that the elbow and its anatomical structure means that the increased flexion accompanied by an increase in internal rotation during CW and RO skills prevents abduction loading of the elbow joint. This finding concurs with Chou, Lou, Chen, Chiu & Chou (2009) who examined elbow load during falling onto an out stretched arm in three hand positions, concluding falls with the forearm internally rotated resulted in a greater elbow flexion and a 50% lower abduction load than those of falls with the forearm externally rotated. Furthermore, previous studies showed that the abduction elbow angle progressively decreased with flexion and may reduce elbow abduction load (Fornalski Gupta, & Lee, 2003; van Roy, Baeyens, Fauvart, Lanssiers, & Clarijs, 2005). Thus, elbow flexion plays an important role in minimizing the risk of impact injury of the elbow joint. In addition, results from the current study indicated that young female gymnasts are at higher risk of elbow joint injury due to an increase in elbow joint abduction load. As for elbow joint compression force, significant differences between sexes were found for CW skills, showing higher magnitudes for female gymnasts compared to males. In addition, significantly higher magnitudes of elbow compression forces were observed between sexes and techniques during RO skills. Combinations of these factors have significant influence on injury potential and are in accordance with previous findings by Koh et al. (1992) who indicated that these compression forces and significantly higher adduction moments placed on the elbow joint during the back handspring may be responsible for chronic injuries. The relationship between this excessive elbow extension and abduction load with elbow injury were highlighted by the cadaveric model of O’Driscoll, Morrey, Korinek, & An (1992) and supported by the clinical examinations of Nork, Hennrikus, Loncarich, Gillingham & Lapinsky (1999). These authors highlighted that supracondylar fractures of the elbow joint in children are a result of extension, valgus load with axial compression force. These three factors (extension, valgus load with axial compression force) are evident in the results of the current study and suggest that a CW and RO in reverse and parallel hand positions can be hazardous techniques especially for young female gymnasts. Another potential cause of injury risk could be from the elbow joint anatomical perspective, through the observation that females show larger elbow carrying angles than males (van Roy et al., 2005), and consequently it can be speculated that young female gymnasts from the current study will have higher abduction loads during weight bearing conditions.

In the current study, significantly higher magnitudes of wrist joint axial compression forces were found in males than females and between different techniques, with the highest magnitude of wrist joint compression force reported in the reverse technique, followed by parallel and T-shape hand positions for both skills (Tables 2 and 3). These findings are in agreement with previous studies (Farana et al., 2017 and 2018) highlighting that in the T-shape hand position, the second contact hand, wrist joint is exposed to lower mechanical loads compared to other techniques for youth male as well as female gymnasts. It has been previously highlighted that repetitive loads placed on the wrist joint can lead to distal radius stress injury (DiFiori, Puffer, Aish & Dorey, 2002; DiFiori et al, 2006). Moreover, evidence from previous research has identified that these compressive loads are transmitted through the carpals to the radius and ulna, with the radius accepting approximately 80% of the load (DiFiori et al., 2002). Finally, in the current study higher peak wrist joint dorsiflexion was found in the T-shape technique compared with the parallel and reverse techniques for both skills and for both sexes. However, these results demonstrated that wrist dorsiflexion for all conditions was lower than the critical value (i.e. >95°) that places the scaphoid at the highest risk for fracture (Weber & Chao, 1978). Conclusions from this study must be considered with the sample size in mind.

However, in order to overcome this, effect sizes were included to provide a measure of the meaningfulness of differences.

Conclusions

Based on the scope and hypothesis of the present study, the findings show that: (1) young female gymnasts exhibited greater peak VGRF, elbow and wrist compression forces and elbow internal adduction moments during CW and RO skills compared with young male gymnasts; (2) in both sexes the parallel and reverse techniques increase peak VGRF, elbow and wrist compression forces and elbow internal adduction moment; (3) increase in elbow flexion resulted in decreased peak VGRF, elbow compression forces and elbow abduction stress. Overall, these findings indicated that the parallel and reverse techniques of CW and RO may increase the potential of elbow and wrist injuries, especially in young female gymnasts. This could be due to differences in elbow joint flexion when increased flexion in young male gymnasts prevents abduction loading. Results from the current study indicated that during CW and RO skills, elbow flexion plays an important role in minimising the risk of impact injury of the elbow. Performing an elbow flexion motion will act as an effective damping mechanism to decrease elbow joint load and further reduce the risk of injury during these fundamental gymnastics skills. Findings from the current study further reinforce and support the use of the T-shape technique for the CW and RO skills in both male and female gymnasts to reduce injury risk associated with these skills. This recommendation is of particular importance due to the high frequency with which these fundamental skills are performed during training and competition.

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Figure 2. *Marker placement on the gymnasts' body.*

Figure 3. *Means and standard deviations for (A) peak ground reaction forces, (B) internal adduction moment, (C) peak elbow flexion angles across all participants for the parallel, reverse and T-Shape techniques during CW skills.*

Figure 4. *Means and standard deviations for (A) peak ground reaction forces, (B) internal adduction moment, (C) peak elbow flexion angles across all participants for the parallel, reverse and T-shape techniques during RO skills.*