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Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike

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Overarm movements are essential skills in many different sport games; however, the adaptations to different sports are not well understood. The aim of the study was to analyze upper-body kinematics in the team-handball throw, tennis serve, and volleyball spike, and to calculate differences in the proximal-to-distal sequencing and joint movements. Three-dimensional kinematic data were analyzed via the Vicon motion capturing system. The subjects (elite players) were instructed to perform a team-handball jump throw, tennis serve, and volleyball spike with a maximal ball velocity and to hit a specific target. Significant differences ($P < 0.05$) between the three overarm movements were found in 17 of 24 variables. The order of the proximal-to-distal sequencing was equal in the three analyzed overarm movements. Equal order of the proximal-to-distal sequencing and similar angles in the acceleration phase suggest there is a general motor pattern in overarm movements. However, overarm movements appear to be modifiable in situations such as for throwing or hitting a ball with or without a racket, and due to differences at takeoff (with one or two legs).

Overarm movements are essential skills in different sport games. In team handball and water polo, players use different throwing techniques to score goals; in volleyball, beach volleyball, and fistball, players hit the ball to score points; in baseball, softball, and cricket, the pitcher/baller will throw the ball at different speeds and/or locations to confuse the hitter; in American football, the quarterback throws the ball over long distances to his receivers to gain yards; and in tennis, badminton, and squash, serves and/or smashes are used to induce pressure on the opposing player to score points. These different overarm techniques for throwing or hitting (with or without a racket) differ either because of the rules of each sport, ball size, and weight or uncontrolled attack strategies of the opposing defensive players. However, these overarm movements may also be similar, especially in the upper-body kinematics between throwing and hitting a ball (with or without a racket). If there are similarities in these different overarm movements, it may be possible to identify general motor patterns of overarm movements that can be adapted to the different sports. The answer to these questions could add important information to understanding of the transfer of movements in the motor learning process and to provide a reference point that is reasonable to practice different overarm movements especially for adolescent or prepubescent athletes.

In previous studies, it was found that a transfer of momentum from proximal to distal is important to maximize performance in javelin (Whiting et al., 1991), baseball (Hong et al., 2001), team-handball throw (Van den Tillar & Ettema, 2009), and tennis serve (Marshall & Elliott, 2000), whereas Wagner et al. (2012) found significant differences in the proximal-to-distal sequence of the maximal joint movements (angular velocities) among different skill levels in team-handball throwing. A positive influence of pelvis, trunk flexion and rotation, shoulder internal rotation, as well as elbow extension to the ball velocity was shown in the baseball pitch (Fleisig et al., 1999; Hong et al., 2001; Stodden et al., 2001), team-handball throw (Van den Tillar & Ettema, 2004, 2007; Wagner et al., 2010), volleyball spike (Coleman et al., 1993), and tennis serve (Elliott et al., 1995; Marshall & Elliott, 2000). However, the shoulder internal rotation angular velocity was identified as the major contributor to the ball velocity and racket speed (Escamilla & Andrews, 2009). Kinematic comparisons between overarm movements in different sports were made between baseball pitching and football passing (Fleisig et al., 1996), as well as between team-handball throwing and volleyball spiking (Bergun et al., 2009). It was found that the different movements were similar but not identical (Fleisig et al., 1996; Bergun et al., 2009). However, in the study of Bergun et al. (2009), kinematics were determined using two cameras, measuring with 50 fps which is insufficient to analyze such dynamic movements to calculate angles or angular velocities. Although studies exist that analyze kinematics and performance in team-handball throw (Van den Tillar & Ettema, 2004, 2007; Wagner et al., 2010), tennis serve (Elliott et al., 1995; Marshall & Elliott, 2000), and volleyball spike (Coleman et al., 1993), studies comparing these movements in detail (angles, angular velocities, and their timing) under similar conditions (game specific movements of elite players on official courts) are missing. Team handball, tennis, and volleyball were selected because they represent typical overarm movements of throwing or hitting a ball (with or without a racket) and where ball velocity is the main performance determining variable and because these sports are played (mostly professionally) all over the world and are part of traditional Olympic Games.

The aims of the study were: (a) to analyze upper-body three-dimensional (3D) kinematics (trunk flexion and rotation, shoulder flexion and internal rotation, as well as elbow flexion) and pelvis rotation in the team-handball jump throw, tennis serve, and volleyball spike of elite players; and (b) to compare the differences in the proximal-to-distal sequence of the maximal joint movements (angular velocities) as well as maximal angles and angular velocities (their timing) between the different overarm movements. We hypothesized there would be differences in maximal angles, angular velocities, and their timing, but similar proximal-to-distal sequencing between the team-handball throw, tennis serve, and the volleyball spike.

Materials and methods

Subjects

Ten male elite team-handball players [mean ± standard deviation (SD) for age: 23 ± 3 years; height: 1.87 ± 0.06 m; weight: 85 ± 10 kg; training experience: 12 ± 3 years; 3 wings, 6 back-court players, 1 pivot, 9 right- and 1 left-handed players], 10 tennis players (mean ± SD for age: 20 ± 4 years; height: 1.88 ± 0.07 m; weight: 77 ± 10 kg; training experience: 14 ± 3 years, 9 right- and 1 left-handed players), and 10 volleyball players (mean ± SD for age: 24 ± 4 years; height: 1.91 ± 0.06 m; weight: 82 ± 8 kg; training experience: 9 ± 4 years; 5 middle blocks, 4 major attackers, 1 setter, 9 right- and 1 left-handed players) participated in the study. All subjects were physically healthy, in good physical condition, and reported no injuries during the time of the study. The study was approved by the local ethics committee and all subjects agreed and signed an informed consent. The subjects were recruited from the Austrian Team Handball National Team ($n = 6$), 2nd and 3rd Austrian Handball League ($n = 4$), male tennis player with an Association of Tennis Professionals ranking better than 347 ($n = 7$), high-performance male youth tennis players with a top 10 national ranking at the time of the study ($n = 3$), and Austrian Volleyball National Team ($n = 2$), 1st and 2nd Austrian Volleyball League ($n = 8$).

Team-handball throw

After a general and a team-handball specific warm-up of 20 min, the subjects performed vertical team-handball jump throws with takeoff from the left leg (right-handed player) or the right leg (left-handed player). The jump throw was selected because this throwing technique is the most frequently applied throwing technique (about 75%) during the game (Wagner et al., 2008). To confirm that the jump throw was a vertical jump throw, the horizontal difference between takeoff and landing may not exceed more than 2 m. The subjects were instructed to throw the ball (International Handball Federation Size 3) at a target from an 8-m distance, and to hit the center of a 1×1 m^2 at about eye level (1.75 m), with maximum ball velocity. The subsequent evaluation was used only for those throws that hit the target. Each subject had to continue to throw until five valid jump throws were achieved. Because the distance between the center of the ball and the hand increases abruptly at the ball release (Van den Tillar & Ettema, 2007; Wagner et al., 2010), to determine the moment of ball release, the distance between the center of the ball and the hand (head of the second metatarsal) was calculated.

Tennis serve

After a general warm-up, the subjects could perform as many practice strokes and services as needed to familiarize themselves with the testing requirement. To enable optimal conditions, the subjects used their own rackets. During testing, the subjects were instructed to serve the ball (flat serve) from left to right into the left side of the service field, with maximum ball velocity. Only those serves that hit the service field were used for the analysis. Each subject had to continue to serve until five flat serves were achieved. Ball contact was defined as the point where the first ball–racket contact occurred. This point was identified with a Basler digital high-speed camera (100 fps) and verified with racket head coordinate data (Landlinger et al., 2010). The racket head horizontal acceleration decreased abruptly at ball–racket contact.

Volleyball spike

Following a general and volleyball specific warm-up of 20 min, subjects performed the required volleyball spikes. To maintain constant testing conditions, the ball was suspended on a rope from the ceiling via an apparatus that held and released the ball when spiked and to allow for similar repeated movement conditions to accommodate players of different jumping height during testing (Wagner et al., 2009). Every subject performed up to three spikes before testing. During testing, subjects were instructed to jump as high as possible and to hit the ball as fast and hard as possible into a 3×3 m corridor on the volleyball court. The subsequent assessment was used only for those spikes that hit the corridor. Subjects had to continue to spike the ball until five hits per subject were achieved. Ball impact was defined as the point where the hand's (head of the second metatarsal) horizontal acceleration of the hitting arm decreased abruptly (cf. ball impact in tennis serve).

Kinematic analysis

The experimental setup consisted of eight cameras of Vicon MX13 motion capture system (Vicon Peak, Oxford, UK). Team-handball jump throw and volleyball spike were captured with 250 fps (Wagner et al., 2009, 2010, 2011), while in the tennis serve the measuring frequency was increased to 400 fps. In the tennis serve, a Basler digital high-speed camera (100 fps) was synchronized with the Vicon MX13 cameras. Therefore, the measuring frequency of Vicon MX13 cameras had to be increased fourfold (400 fps) to accurately measure such a dynamic movement. To compare the three movements, the measuring frequency of the team-handball jump throw and volleyball spike was increased using a spline function in MatLab R14a. For kinematic analysis, 39 reflective markers of 14 mm diameter were affixed to specific anatomical landmarks (Plug-In Gait Marker Set, Vicon Peak) for every participant. Three-dimensional trajectories of the 39 markers were analyzed utilizing Nexus software (Nexus 1.3, Vicon, Oxford, UK) and filtered with a Woltring filter (Woltring, 1986). To calculate the joint positions, a 3D model (Plug-In Gait Model, Vicon Peak) was used (Davis et al., 1991). The model was identical to that used in the team-handball jump throw (Wagner et al., 2010, 2011), tennis ground stroke (Landlinger et al., 2010), and volleyball spike jump (Wagner et al., 2009). The global coordinate system was defined and dependent on the movement direction. The global *x*-axis was defined in the direction of the throw, the *z*-axis vertical and the *y*-axis perpendicular to these axes, whereas the xy-plane was identical with the court. The orientation of the pelvis and trunk segments was identified by calculating three orthogonal axes (*x*-axis anteroposterior, pointed anteriorly; *y*-axis mediolateral, pointed laterally; and *z*-axis longitudinal). The orientations of the humerus, radius, and hand segments were determined by the longitudinal *z*-axis (from the proximal to the distal joint center, pointed distally), the mediolateral *y*-axis (from the distal joint center to the distal joint marker, pointed laterally), and the perpendicular anteroposterior *x*-axis (pointed anteriorly). Joint angles were calculated by the relative orientation of the proximal and distal segments (Figs 1 and 2). The joint flexion angles (shoulder and elbow flexion) were the angles determining the longitudinal axes of the proximal and distal segments. The shoulder internal-external rotation angle was defined as the rotation of the humerus along the longitudinal axis of the humerus, where the rotation of the humerus was determined by the movement of the radius relative to the humerus. Trunk (pelvis) rotation angle was defined as the rotation between the anteroposterior axis of the trunk (pelvis) and the *x*-axis of the global coordinate system. The direction of the rotation was defined as forward (counterclockwise for a right-handed player from an overhead view) and backward rotation (clockwise for a right-handed player from an overhead view), whereas we termed a forward rotation only as rotation. The trunk flexion angle was calculated between the projected anteroposterior trunk axis and the *x*-axis of the global coordinate system. Angular velocities and ball velocity were calculated using the 5-point differential method (Van den Tillar & Ettema, 2003).

Phase classification

To compare different measurements, all throws or hits were time normalized to the ball release or ball contact point. The measurements were conducted from 0.40 s before to 0.10 s after ball release or ball contact to calculate all relevant variables (Coleman et al., 1993; Stodden et al., 2001; Escamilla & Andrews, 2009; Wagner et al., 2009, 2010). Cocking phase, acceleration phase, and follow-through phase were defined as described in Wagner et al. (2010).

Proximal-to-distal sequence and timing

Proximal-to-distal sequence was determined using the time of occurrence of the maximal joint angular velocities (Marshall & Elliott, 2000; Van den Tillar & Ettema, 2009; Wagner et al., 2010). Timing variables were measured relative to ball release or ball contact. A negative value corresponds to a point of time before and a positive value matches with a time after the ball release or ball contact.

Statistical analysis

All statistical analyses were performed using SPSS version 15.0. (SPSS Inc., Chicago, IL, USA). Means and SDs of the variables were calculated for descriptive statistics. Four groups of variables were used for statistical analysis: (a) maximal angular velocity (pelvis and trunk rotation, trunk flexion, shoulder flexion, shoulder internal rotation, and elbow extension); (b) timing of maximal angular velocity; (c) maximal angle (pelvis and trunk rotation, trunk hyperextension, shoulder hyperextension, shoulder external rotation, and elbow flexion); and (d) timing of the maximal angles. Multivariate linear models [multiple analysis of variance (MANOVA)] were calculated to determine if all variables within a group of variables differ significantly between the team-handball throw, tennis serve, and volleyball spike. If the multivariate analysis resulted in a significant difference ($P < 0.05$), one-way analysis of variance (ANOVA) was calculated for all variables within this group. To determine the proximal-to-distal sequence, depending on the different movements (team-handball throw, tennis serve, and volleyball spike), we used a repeated measures two-way ANOVA with timing (pelvis rotation, trunk rotation, trunk flexion, elbow extension, shoulder rotation, and shoulder flexion) and movement (team-handball throw, tennis serve, volleyball spike) as main factors where the term movement is defined as the between-subjects factor. For the MANOVAs and the two-way ANOVA, we used the Bonferroni post hoc test. For all statistic analysis, significance was set at $P < 0.05$ and effect size (η^2) was defined as small for $\eta^2 > 0.01$, medium for $\eta^2 > 0.09$, and large for $\eta^2 > 0.25$ (Cohen, 1988).

Results

Mean ± SD values of maximal angular velocities, timing of maximal angular velocities, maximal angles and timing of maximal angles in the team-handball throw, tennis serve and volleyball spike, the statistical results of the MANOVAs and one-way ANOVAs (global significance, effect size, power), as well as the results of the post hoc tests are depicted in Table 1. Significant differences between team-handball throw, tennis serve, and volleyball spike with a large effect ($P < 0.001$, $\eta^2 > 0.70$, $1\text{-}\beta = 1.00$) were found for all groups of variables used in the analysis. For the single variables, one-way ANOVAs yielded a global significant difference between the different movements for 17 of 24 kinematic variables (Table 1).

The results show the pelvis and trunk rotated more (40–50°) backward in the tennis serve compared with the team-handball throw and volleyball spike in the cocking phase (Fig. 1). This difference was also found in the trunk hyperextension between a tennis serve and the other movements, whereas the trunk was more hyperextended (15–20°) in the volleyball spike compared with the team-handball throw (Fig. 2). For maximal angular velocities, pelvis rotation, trunk flexion, and trunk rotation were higher (50–250°/s) in the tennis serve compared with the team-handball throw and volleyball spike. Maximal shoulder hyperextension angle (10–20°) and shoulder flexion angular velocity (150–550°/s) were greater in the team-handball throw compared with the tennis serve and volleyball spike. No significant differences between the analyzed movements were found in the maximal shoulder external rotation angle, shoulder internal rotation angular velocity, and elbow extension angular velocity.

Analyzing the proximal-to-distal sequencing, it was found that the maximal angular velocities occurred from proximal to distal beginning with the pelvis rotation,

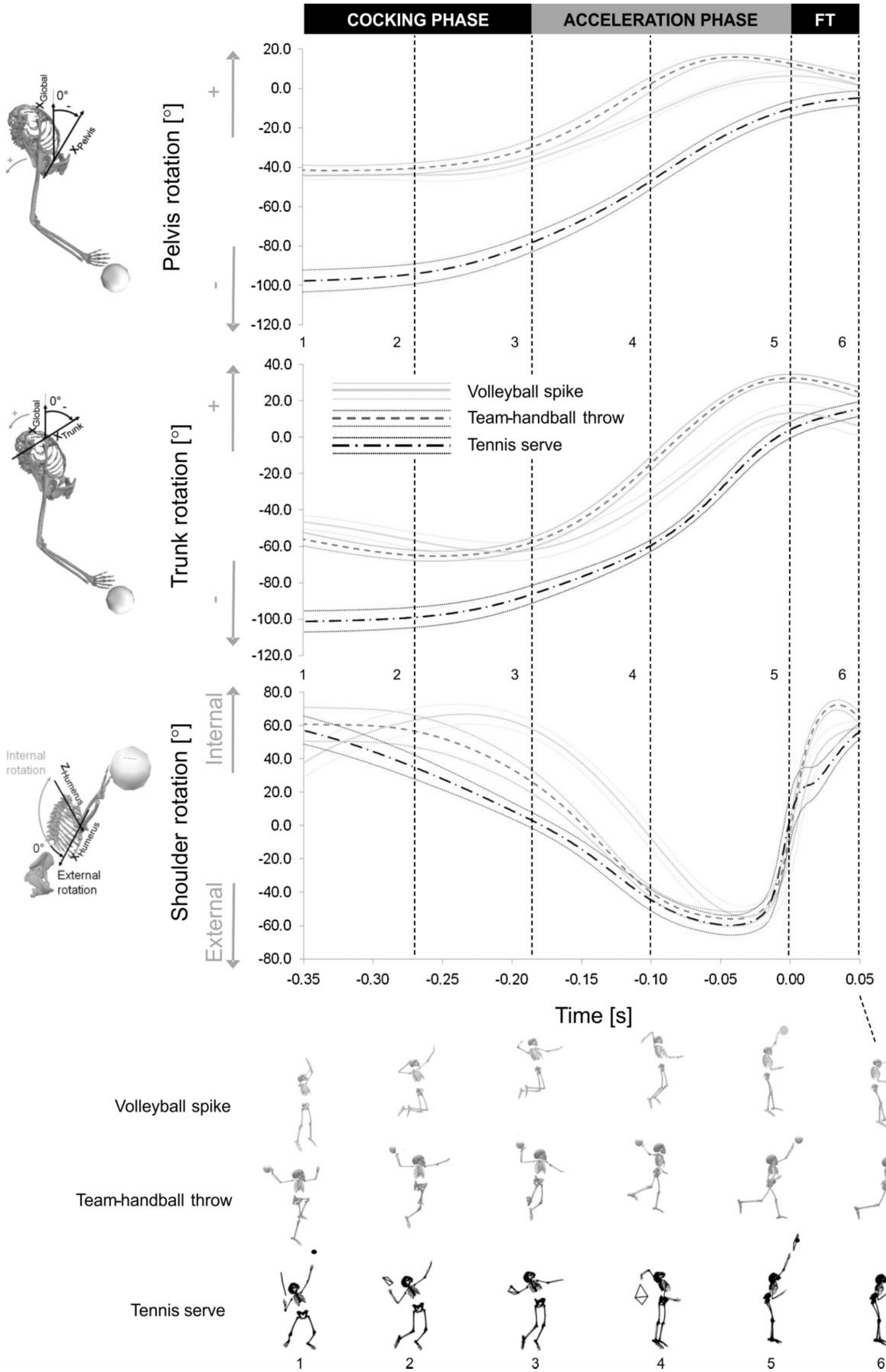

Fig. 1. Mean (± standard error) pelvis, trunk, and shoulder rotation angle in the team-handball throw, tennis serve, and volleyball spike. FT, follow-through.

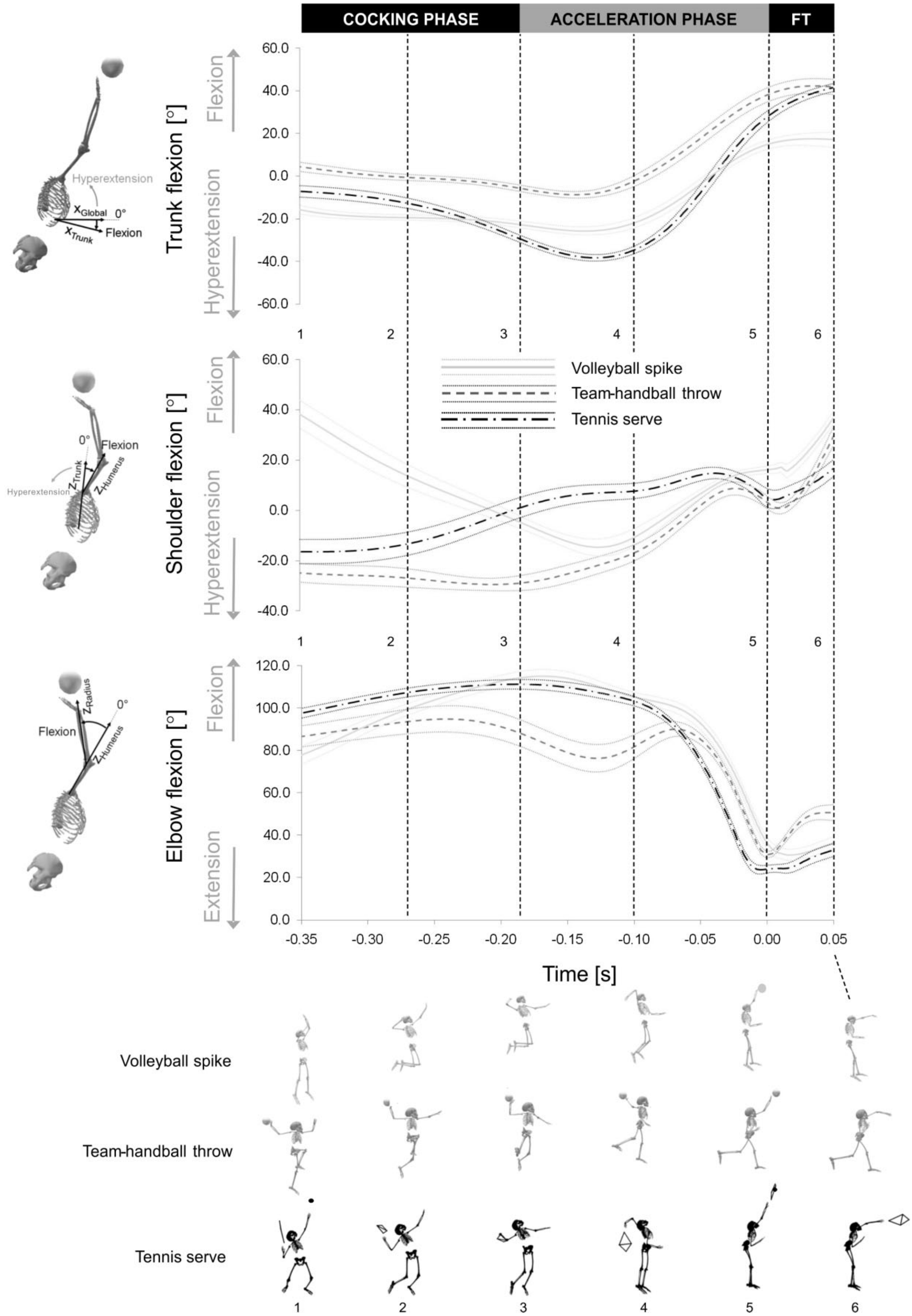

Fig. 2. Mean (± standard error) trunk, shoulder, and elbow flexion angle in the team-handball throw, tennis serve, and volleyball spike. FT, follow-through.

Table 1. Maximal angles and angular velocities (and their timing relative to ball release or ball contact) of the pelvis, trunk, shoulder, and elbow (rotation and/or flexion) in the team-handball throw, tennis serve, and volleyball spike, and associated significant differences

	Team handball	Tennis	Volleyball	Global significance	η^2	Power
Maximal angular velocity (°/s)				< 0.001	0.84	1.00
Pelvis rotation	450 ± 120	510 ± 110	370 ± 90	< 0.05[c]	0.23	0.67
Trunk flexion	480 ± 60	910 ± 130	490 ± 110	< 0.001[ac]	0.81	1.00
Trunk rotation	740 ± 70	880 ± 140	640 ± 160	< 0.01[ac]	0.41	0.97
Shoulder flexion	1100 ± 240	590 ± 140	920 ± 130	< 0.001[ac]	0.61	1.00
Shoulder internal rotation	4700 ± 850	5580 ± 2350	4520 ± 1020	0.29	0.09	0.26
Elbow extension	1570 ± 230	1670 ± 380	1600 ± 520	0.84	0.01	0.08
Timing of maximal angular velocity (s)				< 0.001	0.72	1.00
Pelvis rotation	–0.118 ± 0.018	–0.081 ± 0.028	–0.113 ± 0.032	< 0.05[ac]	0.29	0.81
Trunk flexion	–0.047 ± 0.013	–0.042 ± 0.011	–0.045 ± 0.010	0.60	0.04	0.13
Trunk rotation	–0.089 ± 0.017	–0.045 ± 0.012	–0.063 ± 0.013	< 0.001[abc]	0.63	1.00
Shoulder flexion	0.050 ± 0.008	0.063 ± 0.050	0.050 ± 0.009	0.15	0.13	0.38
Shoulder internal rotation	0.003 ± 0.003	–0.005 ± 0.011	0.005 ± 0.003	< 0.01[ac]	0.32	0.87
Elbow extension	–0.020 ± 0.018	–0.030 ± 0.005	–0.016 ± 0.008	< 0.05[c]	0.20	0.59
Maximal angle (°)				< 0.001	0.91	1.00
Pelvis rotation (–)	–43 ± 9	–99 ± 17	–48 ± 8	< 0.001[ac]	0.83	1.00
Trunk hyperextension	10 ± 4	39 ± 5	27 ± 7	< 0.001[abc]	0.84	1.00
Trunk rotation (–)	–66 ± 9	–102 ± 18	–64 ± 16	< 0.001[ac]	0.61	1.00
Shoulder hyperextension	35 ± 7	21 ± 11	17 ± 10	< 0.01[ab]	0.42	0.97
Shoulder external rotation	58 ± 12	61 ± 19	55 ± 25	0.77	0.02	0.09
Elbow flexion	100 ± 17	112 ± 8	117 ± 9	< 0.05[b]	0.28	0.78
Timing of maximal angle (s)				< 0.001	0.70	1.00
Pelvis rotation	–0.310 ± 0.064	–0.333 ± 0.047	–0.300 ± 0.055	0.40	0.07	0.20
Trunk hyperextension	–0.199 ± 0.020	–0.099 ± 0.011	–0.119 ± 0.020	< 0.05[a]	0.25	0.71
Trunk rotation	–0.234 ± 0.020	–0.315 ± 0.057	–0.186 ± 0.019	< 0.001[abc]	0.70	1.00
Shoulder hyperextension	–0.211 ± 0.075	–0.238 ± 0.077	–0.130 ± 0.050	< 0.001[bc]	0.48	0.99
Shoulder extension rotation	–0.029 ± 0.016	–0.010 ± 0.014	–0.016 ± 0.005	< 0.01[a]	0.31	0.84
Elbow flexion	–0.156 ± 0.108	–0.171 ± 0.040	–0.141 ± 0.041	0.65	0.03	0.11

[a]Between team-handball throw and tennis serve.
[b]Between team-handball throw and volleyball spike.
[c]Between tennis serve and volleyball spike.

followed by the trunk rotation, trunk flexion, elbow extension, shoulder internal rotation, and shoulder flexion in all three movements (Fig. 3). Repeated measures two-way ANOVAs yielded a significant effect for timing ($F(23,5) = 270$, $P < 0.001$, $\eta^2 = 0.98$, $1\text{-}\beta = 1.00$), movement ($F(27,2) = 6.4$, $P < 0.01$, $\eta^2 = 0.32$, $1\text{-}\beta = 0.87$), and the timing × movement interaction ($F(46,10) = 8.5$, $P < 0.001$, $\eta^2 = 0.65$, $1\text{-}\beta = 1.00$). Time of occurrence of the maximal angular velocities differed and was highly significant ($P < 0.001$) to each other and significant differences between the different movements in the timing were found in the pelvis rotation, trunk rotation, shoulder internal rotation, and elbow extension (Table 1).

Discussion

The aim of the study was to analyze not only differences but also similarities in the upper-body kinematics between the team-handball throw, tennis serve, and volleyball spike. For a detailed discussion of the results, the discussion was separated into different parts based on technical and tactical components as well as different lower body movements that could influence possible differences in the upper-body kinematics.

Jumping vs. standing

It is well known that the team-handball jump throw, tennis serve, and volleyball spike differ in lower body movements. The team-handball jump throw involves executing a vertical jump off one leg at takeoff after the run-up, whereas the main part of the throwing movement is executed during the flight phase. This is also true in the volleyball spike, except that the takeoff is done with both legs. In the tennis serve, the first part of the cocking phase is done during standing; in the second part of the cocking phase, tennis players executed a jump-off with both legs (0.27 ± 0.02 s before ball contact). During cocking phase, the pelvis and trunk were rotated backward in all three analyzed movements (Fig. 1), whereas the backward rotation angle of the pelvis (50–60°) and trunk (30–40°) rotation were greater in the tennis serve compared with the team-handball throw and volleyball spike. We observed that the floor contact in the tennis serve enabled a greater rotation over the front leg followed by a longer time for acceleration of the trunk and pelvis rotation. This allowed for generating greater maximal angular velocity of the pelvis (10–40%) and trunk (15–45%) rotation in the tennis serve compared with the team-handball throw and volleyball spike. In different team-handball throwing techniques (Wagner

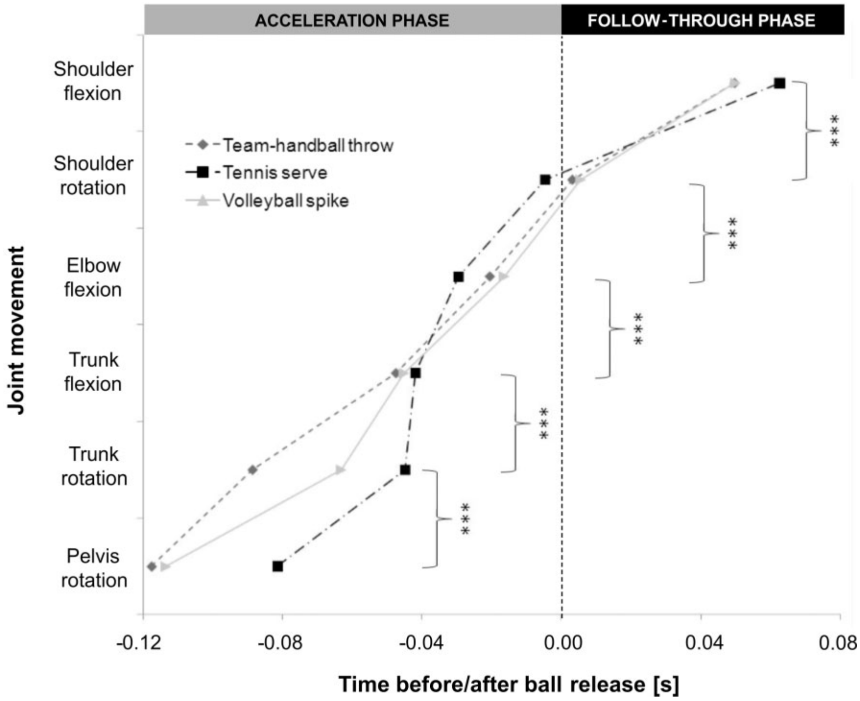

Fig. 3. Mean timing of maximal angular velocities in the team-handball throw, tennis serve, and volleyball spike. Significant differences between two joints: $*P < .05$, $**P < .01$, $***P < .001$.

et al., 2011), it was shown that the maximal pelvis and trunk rotation backward angle during the cocking phase and maximal pelvis and trunk rotation angular velocity during acceleration phase differ significantly between standing (with and without run-up) and jumping (takeoff on one or both legs) throws. In the jump throws, team-handball players had to rotate the trunk and pelvis via opposed leg movements during the flight. Pelvis and trunk rotation angle and angular velocity are similar in the tennis serve and in a team-handball standing throw (with and without run-up) but are quite different to a team-handball jump throw or volleyball spike. We observed that the floor contact during cocking has a strong influence on pelvis and trunk rotation in overarm movements.

Proximal-to-distal sequencing

We hypothesized that there would exist a similar proximal-to-distal sequencing in the different overarm movements. As shown in Fig. 3, maximal angular velocities occurred in a specific proximal-to-distal order starting with pelvis rotation followed by trunk rotation, trunk flexion, elbow extension, shoulder internal rotation, and shoulder flexion in all analyzed overarm movements. This order of occurrence is typical for overarm movements and was also found in similar studies (Whiting et al., 1991; Fleisig et al., 1999; Marshall & Elliott, 2000; Hong et al., 2001; Van den Tillar & Ettema, 2009; Landlinger et al., 2010; Wagner et al., 2012). The proximal-to-distal sequencing was specific because the maximal elbow extension angular velocity occurred before the maximal shoulder internal rotation angular velocity. We ascertain that the elbow of the throwing or hitting arm was extended earlier to reduce the moment arm for the shoulder internal rotation (Hong et al., 2001; Van den Tillar & Ettema, 2004; Wagner et al., 2012), and elbow extension angular velocity was reduced to prevent excessive extension of the elbow and therefore reduce the possibility of muscle and joint injuries (Wierzbicka et al., 1986; Wagner et al., 2012). The highest elbow extension angle and therefore the smallest moment arm for the shoulder internal rotation was measured near ball release or contact (Fig. 2) when the shoulder internal rotation angular velocity reached its maximum (Table 1). The order of occurrence was identical between the different analyzed overarm movements; only the timing was significantly different. As shown in Fig. 3 and Table 1, maximal pelvis and trunk rotation angular velocity occurred later in the tennis serve compared with the team-handball throw and volleyball spike. We suggest that the longer time of acceleration of the pelvis and trunk rotation enabled a higher but delayed maximal angular velocity in the tennis serve compared with the team-handball throw and volleyball spike (Fig. 4).

The influence of ball and racket

The maximal elbow extension and shoulder internal rotation angular velocity occurred earlier in the tennis

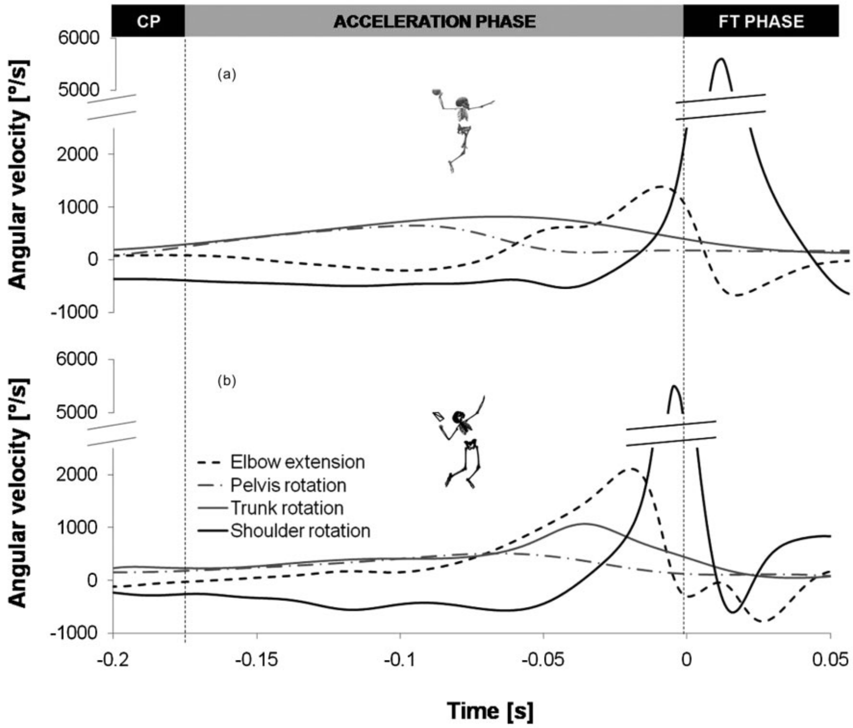

Fig. 4. Example of pelvis rotation, trunk rotation, elbow extension, and shoulder internal rotation angular velocity in the team-handball throw (a) and tennis serve (b). CP, cocking phase; FT, follow-through.

serve compared with the team-handball throw and volleyball spike (Table 1 and Fig. 3). We maintain that the tennis racket influences those significant differences in timing. In the last sequence of the tennis serve, the racket has to be accelerated. The shoulder internal rotation angular velocity was reduced and momentum was transferred from the upper and lower arms to the racket (Elliott et al., 1995; Marshall & Elliott, 2000). Another aspect is the weight of the tennis racket and handball. In the tennis serve and team-handball throw, the throwing arm must accelerate the additional weight of the tennis racket or handball whereas in the volleyball spike there is no additional weight that has to be accelerated. We found significant differences in the maximal angular velocities of pelvis rotation, trunk rotation, and trunk flexion between the tennis serve and team-handball throw as well as volleyball spike, but no significant differences in the maximal shoulder internal rotation and/or elbow extension angular velocity. We suggest that the transfer of momentum from the trunk to the throwing arm compensates for the different angular momentum due to the tennis racket or handball. The difference in the angular momentum due to the tennis racket may also explain the reduced and delayed maximal angular velocity of shoulder flexion in the tennis serve compared with the team-handball throw and volleyball spike.

The influence of arm swing at takeoff in the volleyball spike

In the volleyball spike jump, the left and right shoulder flexion angular velocities were maximized during the upward phase to potentially increase jump height (Escamilla & Andrews, 2009; Wagner et al., 2009). The differences in the shoulder internal rotation and shoulder flexion angle in the cocking phase of the volleyball spike compared with the tennis serve and team-handball throw (Figs 1 and 2) are probably due to this shoulder flexion at takeoff that leads to a delay in the maximal shoulder hyperextension angle in the volleyball spike jump. However, volleyball players were able to adapt to these differences that lead to a similar shoulder internal rotation and shoulder flexion angle in the acceleration phase.

The influence of impact from an opposing player in team-handball throwing

In the tennis serve, the initiation of the movement is decided by the player and the movement cannot be disturbed by the opposing player. In the volleyball spike, initiation of the movement is often influenced by the setter and the movement of opposing players albeit not disrupting the actual movement. In team handball, however, the throwing player is often tackled by the opposing defensive player to prevent the throw. Wagner et al. (2010) have reported significant differences in the trunk flexion between elite and low-level players in team-handball jump throw. The authors suggested that elite players have adapted their throwing movement to prevent the impact of the opposing defensive player to prevent injuries. Gutierrez Davila et al. (2006) analyzed the effect of opposition on the team-handball jump throw in elite players and found no significant differences in the upper-body kinematics between throwing with or without impact of an opposing defensive player. We report that the elite team-handball players in this study may have already habitually adopted this trunk movement and have exhibited the movement also during testing. Therefore, the maximal trunk hyperextension was lower in the team-handball throw (10 ± 4°) compared with the tennis serve (39 ± 5°) and volleyball spike (27 ± 7°). We suggest that the higher maximal trunk hyperextension allows more time for acceleration during trunk flexion, and therefore a higher (70–100%) maximal trunk flexion angular velocity in the tennis serve compared with the team-handball throw and volleyball spike. Similar results were found when comparing football passing (possible tackling from an opposing player) with baseball pitching (Fleisig et al., 1996).

Similarities between the different overarm movements

We found adaptations in the three different overarm movements as a result of jumping vs. standing, the influence of a ball and/or racket of the arm swing at takeoff in the volleyball spike, as well as the impact from an opposing player in team-handball throwing. However, the results of our study also show that there is a general motor pattern in overarm movements of throwing or hitting a ball (with or without a racket). These overarm movements are characterized by the pelvis and trunk backward rotation as well as shoulder hyperextension and elbow flexion at the beginning of the cocking phase, followed by the trunk hyperextension at the end of the cocking phase (Figs 1 and 2). Acceleration started with the pelvis rotation, followed by the trunk rotation and trunk flexion (Figs 1–4). During this phase, the shoulder was rotated externally. Ball (in the team-handball throwing), racket (in the tennis serve), or hand (in the volleyball spike) were then accelerated by the shoulder internal rotation added by the elbow extension, whereas the shoulder internal rotation angular velocity was absolutely greatest in all overarm movements compared with the other angular velocities. As shown in Fig. 1, shoulder internal rotation angle is similar in the team-handball throw, tennis server, and volleyball spike. The results of this study are in agreement with kinematic studies in other overarm movements like football passing and baseball throwing (Fleisig et al., 1996). We assert that elite team handball, tennis, and volleyball players are able to reach a high ball velocity in all different overarm movements in team handball, baseball, softball, cricket and water polo throwing, volleyball, beach volleyball and fistball hitting, as well as tennis, badminton, and squash serving or smashing. Studies that analyze this transfer of movements (the same athletes in different overarm movements) are warranted.

Perspectives

The team-handball throw, tennis serve, and volleyball spike show an equal order in the proximal-to-distal sequence of the maximal angular velocities as well as similar angles in the pelvis, trunk, and throwing or hitting arm movements. The overarm movements differ in the range of motion and therefore in the time of acceleration of the pelvis and trunk rotation depending on the ground contact, in trunk flexion depending on possible impacts of the opposing player in competition (in team handball), and in shoulder flexion and rotation depending on the arm movements at takeoff (in the volleyball spike). We conclude that the overarm movements are similar but not identical, because there are specific adaptations based on technical and tactical components of different games as well as different lower body movements. However, training with other overarm movements may be beneficial, especially for adolescent and prepubescent athletes.

Key words: 3D kinematics, angular velocity, similarity of movements, specific differences.

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