A Biomechanical Analysis of Clear Strokes in Badminton Executed by Youth Players of Different Skill Levels

by Kasper Sørensen

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Abstract

Several studies have emphasized the importance of certain phenomenas when skilled athletes perform throwing or hitting tasks. Such phenomenas include the longitudinal axis rotations of the upper arm and forearm and the proximal-distal sequencing of the involved segments. The aim of the present study was investigate biomechanical differences in stroke technique between youth badminton players of different skill levels, where the afore-mentioned phenomenas were subject to the analysis. The forehand and backhand clear strokes were chosen for the analysis. A total of 20 subjects participated in the study; 10 skilled players and 10 less skilled players. Reflective spherical markers were attached to the subject's body and the racket. The data was recorded using a motion capture system consisting of eight high-speed cameras sampling at a frame rate of 500 Hz. The results showed that both types of subjects executed the forehand clear stroke much the same way, whereas the technique in the backhand clear stroke was quite differently. The longitudinal axis rotations reached the highest angular velocities of all joint movements, supporting the idea that such joint movements may play a crucial role in producing high racket head speeds. The skilled players reached significantly higher angular velocities for the glenohumeral external rotation, elbow supination and wrist extension in the backhand stroke. However, no such differences were found in the forehand stroke. Both types of subjects utilized a proximal-distal sequence in the forehand clear stroke, with regards to peak joint powers from joint reaction forces. As a consequence, they transferred a significant amount of energy from the proximal segments to the distal segments via joint reaction forces. Regarding the backhand clear stroke, the skilled players utilized a proximal-distal sequence, whereas the less skilled players deviated from this in some way. As a result, the skilled players transferred a significantly greater amount of energy to the distal segments due to joint reaction forces.

1 Introduction

Highly ranked youth badminton players seem to have a different stroke technique compared to lower ranked players. However, it can be difficult to discover the exact difference in the execution when observing them in a training session. This might be due to the complexity and velocity of the movement. The complexity is reflected in the many degrees of freedom in the involved joints and the different coordination possibilities. A racket head speed of 50 m/s has been measured during a badminton smash (Liu et. al., 2002; Kwan et. al.; 2010; Rasmussen et. al., 2010) illustrating a high-speed movement. In view of this, it would be of great interest to create guidelines to help skill improvement.

There is a lack of scientific research in badminton, including biomechanical investigations of stroke techniques (Liu et. al., 2002). Most studies dealing with this subject have been focusing on a forehand badminton smash. This makes the application of the findings rather limited since the strokes are executed quite differently. In the present study the aim is to examine biomechanical differences in stroke technique between youth players of different skill level. The concepts of interest are the employment of specific joint movements and the proximal-distal coordination. The overhead forehand and backhand clear stroke were subject to the analysis. These strokes have been selected for several reasons. Firstly, clear strokes are among the most common strokes in badminton (Ming et. al., 2008), and they provide the basis of playing the shuttle from the players' own backline to the opponent's backline. Secondly, the purpose of the strokes are similar, yet the execution seems quite different. In particular, less skilled players seem to have trouble creating adequate speed of the racket head, when they perform a backhand clear stroke. Thirdly, no previous study has investigated the movement of these strokes.

Despite the lack of scientific research in badminton, results in related sports exist. Studies concerning tennis, squash, team handball and pitching have given additional insight and explanations of the above-mentioned concepts (Marshall and Elliott, 2000; Elliott et. al., 1996; Tillaar and Ettema, 2009; Hirashima et. al., 2008).

Tang et. al. (1995) investigated the movement at the radio-ulnar joint and the wrist joint in a badminton smash. They concluded that since the pronation of the radio-ulnar joint had the greatest range of motion in the shortest time, this joint action could be important for making a rapid smash. However, this study seems insuffient because it did not consider the movement of the thorax and the glenohumeral joint. A study, done by Liu et. al. (2002) on seven female elite players, did however consider the movement of the glenohumeral joint during a badminton smash. They concluded, that the glenohumeral internal rotation had the highest angular velocity of 74 rad/s followed by the elbow pronation of 68 rad/s and the hand flexion of 14 rad/s. Applying the three-dimensional kinematic model by Sprigings et. al. (1994), they calculated the contributions of each segmental rotation of the arm to the final speed of the racket head. The results showed that the main contributors were the glenohumeral internal rotation (66%), the elbow pronation (17%) and the hand flexion (11%).

Similiar studies dealing with tennis and squash have been done (Elliott et. al., 1995; Elliott et. al., 1996) both of which resembles the movement in a forehand stroke in badminton. Both studies observed high angular velocities in the internal rotation of the upper arm and forearm just before impact. Moreover, the wrist flexion also showed a high angular velocity. These three movements were again among the main contributors to the final speed of the racket head using Sprigings' model (Marshall and Elliott, 2000).

All these results solely concern the magnitude of certain rotations and did not consider the intersegmental coordination of the stroke over time. Thus, to get a profound analysis of stroke techniques one would have to consider the proximal-distal sequence (Hirashima and Ohtsuki, 2006; Hirashima et. al., 2008; Putnam, 1993). This concept yields that the movement should start with large, heavy and slow central body segments proceeding outward to smaller, lighter and faster segments (Marshall and Elliott, 2000; Putnam, 1993). Obviously, this whiplash type of motion is employed in many sports dealing with throwing or hitting objects (Tillaar and Ettema, 2009; Putnam, 1993). Consequently, research have been done in order to identify this sequence in different sports and describe the kinetic advantages of such a movement.

However, it is not obvious how this proximal-distal sequence should be identified (Putnam, 1993) and thus many methods have been applied (Tillaar and Ettema, 2009). This includes the timing of the maximal linear velocity of the distal endpoints of each segment, the maximal angular velocities of the joint movements and the initiating of the angular velocities of the joint movements. Some studies had trouble determining a proximal-distal sequence, e.g. team handball (Tillaar and Ettema, 2009). Tillaar and Ettema (2009) found a later occurence of the maximal linear velocity of the trunk compared with the upper arm. Furthermore, looking at the maximal angular velocity of the joint movements, they concluded that the wrist flexion occured before elbow extension, and that the latter occured before the upper arm internal rotation. Similiar findings were reported in tennis and squash where the glenohumeral internal rotation and elbow pronation reached peak values after that of the glenohumeral flexion, glenohumeral abduction and elbow extension (Marshall and Elliott, 2000). Some of these results seem valid for a badminton smash as well (Liu et. al., 2002). In fact, Marshall and Elliott (2000) concluded, that the traditional proximal-distal sequencing concepts seem inadequate to describe the complexity of some movements (Marshall and Elliott, 2000, p. 247). However, Tillaar and Ettema (2009) emphasized, that their results do not undermine the proximal-distal principle since the principle "is based on the fundamental idea that a progression of limb segmental motion from proximal to distal must occur to profit optimally from reactive forces between segments when producing maximal speed of the distal segment" (Tillaar and Ettema, 2009, p. 953).

In the present study we will examine the proximal-distal sequence in relation to the energy transfer between segments caused by joint reaction forces, as suggested by Tillaar and Ettema. It seems unlikely that the high angular velocities produced in certain high-speed throwing and hitting tasks can be produced by human muscles, thus suggesting an energy transfer from the proximal segments. The method has been applied by Rasmussen et. al. (2010) on a badminton smash executed by an olympic badminton player. The results showed a proximal-distal sequence with respect to the peak powers, from joint reaction forces, transferred over the joints. At first the glenohumeral joint peaked followed by the elbow and wrist joint, respectively. Rasmussen et. al. (2010) concluded, that the peak power at the wrist reached values around 1 kW. In addition they stated, that such values are not possible to generate by a contraction at the wrist joint alone, and consequently energy must be tranferred from the more proximal segments.

Corresponding results have been observed in pitching in baseball by Hirashima et. al. (2008). They examined how the angular velocity at each joint were obtained by coordinating the joint torque and a velocity-dependent torque. Using the method of forward dynamics, they determined the joint accelerations caused by these torques. They concluded, that the baseball players accelerates the elbow and wrist joint rotations by utilizing the velocity-dependent torque that was originally produced by the proximal trunk and shoulder joint torques in the early phase (Hirashima et. al., 2008, p. 2874).

In the light of the preceding article review and the author's own observations, it seems reasonable that skilled players will produce higher angular velocities of the glenohumeral internal rotation, elbow pronation and wrist flexion in the execution of the forehand clear stroke compared to the less skilled players. This idea could be applicable to the backhand clear stroke as well. Furthermore, it would be reasonable that skilled players, to a greater extent, utilize a proximal-distal sequence compared to the less skilled players, thus having a greater energy transfer due to joint reaction forces. To compensate for the possible smaller energy transfer, the less skilled players may perform more joint work from the joint torques. Consequently, the purpose of the present study is to test the following hypotheses:

- **Kinematic analysis**: Regarding the forehand clear stroke, the skilled youth players generate significantly higher maximal angular velocities in the following joint movements: Glenohumeral internal rotation, elbow pronation and wrist flexion. Equivalently, for the backhand clear stroke: Glenohumeral external rotation, elbow supination and wrist extension. Moreover, the time occurence of these maximal angular velocities will be significantly different between the two types of subjects.
- **Joint power and joint work**: Skilled youth players utilize a proximal-distal sequence as regards to the peak joint powers from the joint reaction forces. As a consequence, the skilled players will have a different net change of energy in the segments compared to the less skilled players. Hence, they will produce significantly higher maximal segment energies, from the joint reaction forces, for the distal segments: Forearm, hand and racket handle. In contrary, the less skilled players will produce a significantly larger absolute joint work, from the joint torques, at all of the involved joints.

All hypotheses stated provides that there is no significant difference in the mean racket head speed at impact.

2 Method

2.1 Subjects

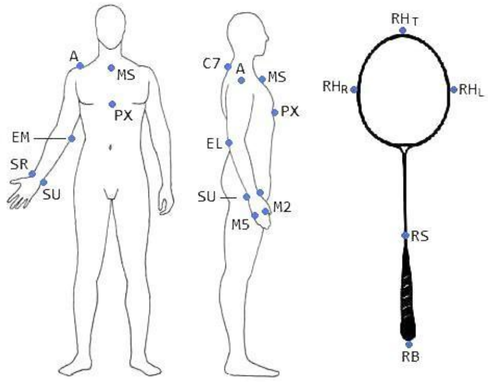
A total of 20 male subjects, aged between 13-14, were chosen for the study; 10 subjects were skilled elite players (group A) and 10 subjects were less skilled players (group B). Their skills were reflected in a Danish ranking system: Elite (E), Master (M), A, B and C (DBF, 2010). There was no significant difference in years of experience with badminton between the two groups, where the mean values were calculated to 5.7 and 5.1 years for groups A and B, respectively ($p = 0.535$). The body mass and height of the two groups were similar as well (p = 0.867 and p = 0.333). An informed consent was obtained from all subjects. The most important data is summarized in Table 1.

Subject (Group A)	Age (yr)	Ranking E-M-A-B-C	Body Mass (kg)	Height (m)	Subject (Group B)	Age (yr)	Ranking E-M-A-B-C	Body Mass (kg)	Height (cm)
1	13	E	41.1	1.53	1	13	B	50.7	1.71
2	13	E	55.0	1.61	2	13	B	37.7	1.49
3	13	E	54.7	1.65	3	13	B	34.4	1.49
4	13	M	46.6	1.57	4	13	B	57.9	1.61
5	13	M	47.3	1.59	5	13	B	59.7	1.67
6	13	M	54.8	1.66	6	13	B	58.1	1.81
7	14	E	56.1	1.80	7	14	C	54.0	1.76
8	13	M	36.6	1.47	8	14	C	54.3	1.72
9	14	E	46.0	1.66	9	14	C	55.2	1.75
10	14	E	67.2	1.70	10	14	C	50.0	1.68
Mean $\pm$ SD	13.3 $\pm$ 0.48	N/A	50.5 $\pm$ 8.78	1.62 $\pm$ 0.09	Mean $\pm$ SD	13.4 $\pm$ 0.52	N/A	51.2 $\pm$ 8.59	1.67 $\pm$ 0.11

Table 1: Age, ranking, body mass and height of all the participating subjects. Subjects within group A are stated to the left, while subjects in group B are stated to the right. N/A = Not available.

2.2 Experimental setup and protocol

The motion capture data was recorded using a Qualisys Oqus 300 system (Gothenburg, Sweden) which consisted of eight high-speed cameras sampling at a maximum frame rate of 500 Hz. The high frame rate was necessary to capture the majority of the high-speed racket movement. Reflective spherical markers were attached at landmarks on the subject's body, as shown in Figure 1. In addition five markers were attached to the racket.



Marker	Landmark
MS	Manubrium Sterni
PX	Processus Xiphoideus
C7	C7
A	Acromion
EL	Epicondylus Lateralis
EM	Epicondylus Medialis
SR	Pr. Styloideus Radii
SU	Pr. Styloideus Ulnae
M2	Metacarpophalangeal II
M5	Metacarpophalangeal V
RB	Racket bottom
RS	Racket shaft
RH$_R$	Racket head (right)
RH$_L$	Racket head (left)
RH$_T$	Racket head (top)

Figure 1: The placement of spherical markers on the body and the racket.

The subjects were placed in the middle of the laboratory (area S), surrounded by the eight cameras. Four cameras (C2, C4, C6 and C8) were placed on tripods to capture the lower part of the racket movement while the remaining cameras (C1, C3, C5 and C7) were mounted on wall brackets to capture the higher part. An assistant was set to throw shuttles from area T. The setup is illustrated in Figures 2 A and B.

For each subject 10 successful forehand and 10 succesful backhand clear strokes were recorded. Before each recording the subject and the assistant had 20 trials to get comfortable with the throw-stroke sequence and the setup. The subjects were asked to perform the clear strokes with the same speed, they usually apply in a match, in which they enable the shuttle to fly from the player's own backline to the opponent's backline. If however they were not able to generate adequate speed, they were told to hit as hard as possible. The order of the two stroke types was randomized. All subjects used the same top-model racket from FZ Forza, Kevlar N-Power 160 TR (Active Sportswear A/S, Bronderslev, Denmark).

The data was tracked using the software Qualisys Track Manager (QTM) and was exported as C3D-files for later use. The calculated mean calibration error was 0.8823.

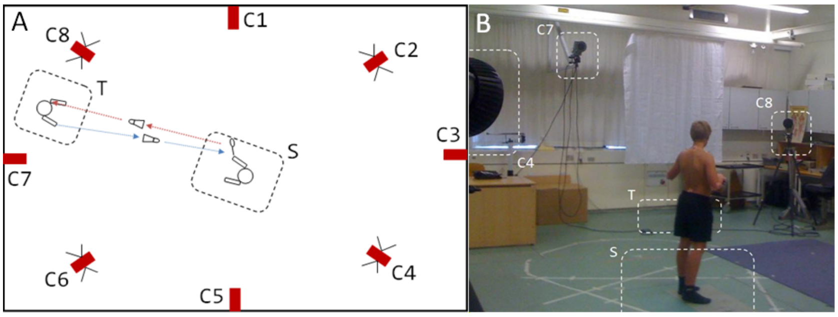


Figure 2: The experimental setup with the high-speed cameras, stroke area and throwing area.

2.3 Data Analysis

The data analysis was mainly carried out using the The AnyBody Modeling System 4.2.1 (AnyBody Technology A/S, Aalborg, Denmark), where the data was imported through a zero-phase, fourth order Butterworth filter with a cutoff frequency of 20 Hz. The software system is used for simulating the mechanics of the human body working in the surrounding environment. The system allows both a kinematic and kinetic analysis of the movement (Damsgaard et. al., 2006). The system is based on a skeletal model in which the muscles are represented as torque providers in the joints. The skeletal model was driven by the exported C3D-files from QTM. The multi-segment model consisted of the thorax, the upper limb and a racket. The shoulder model was based on an already validated model by Van der Helm (1992). To allow certain computations the hand-racket connection was modelled as a spherical joint. The mass and inertia properties of the model was scaled according to the height, body mass and marker position of each subject (Table 1). This proces was done by performing a parameter optimization study in The AnyBody Modeling System (Andersen et. al., 2009). Figure 3 A illustrates the skeletal model.

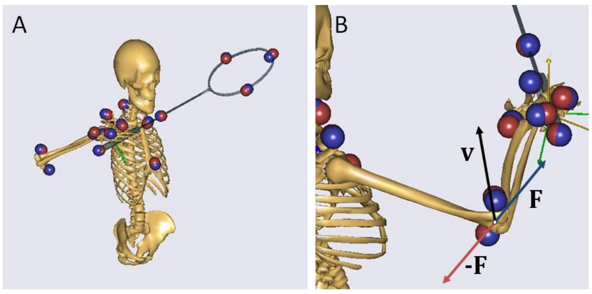


Figure 3: A) The skeletal model in The AnyBody Modeling System. B) The joint forces, $\mathbf{F}$ and $-\mathbf{F}$, and the linear velocity ($\mathbf{v}$) of the elbow joint center.

The kinematic analysis computed all angular positions, velocities and accelerations of the segment and joint movements. Hereof all angular velocities, beside the movement of the scapula, were selected as output. Mean values of the maximal angular velocities of the segment and joint movements were calculated using Microsoft Office Excel 2007 (Redmond, Seattle, USA). Here the "segment movements" refers to the thorax which moved with respect to the global reference frame. The time occurences of the maximal angular velocities were calculated to analyze the coordination.

As for the kinetic analysis the following considerations and actions were made. Power is transferred over joints by joint torques and by joint reaction forces where the former is generated by active muscle forces. The joint power (P_{m}) of a joint torque is calculated as the scalar product (Zatsiorsky, 2002):

$$P_{\text{m}} = \mathbf{T} \cdot \boldsymbol{\omega},$$

where the three-dimensional vector $\mathbf{T}$ is the joint torque and $\boldsymbol{\omega}$ is the relative angular velocity at a joint. The sign determines whether the contraction is concentric or excentric where a positive sign denotes a concentric muscle action. To determine the joint work of a joint torque (W) during a period from t_1 to t_2, one should calculate the time integral of the joint power:

$$W\Big|_{t_1}^{t_2} = \int_{t_1}^{t_2} P_{\text{m}} \, dt.$$

Since we are interested in determining the total amount of energy produced by the muscle torque, the absolute joint work (W_{abs}) is of great interest:

$$W_{\text{abs}}\Big|_{t_1}^{t_2} = \int_{t_1}^{t_2} |P_{\text{m}}| \, dt.$$

The AnyBody Modeling System contains an inherent function that calculates the joint powers produced by the muscles for each degree of freedom. From this we determined the joint power at the glenohumeral, elbow, wrist and hand-racket joint. To calculate the absolute joint work, numerical integration was applied in Microsoft Office Excel 2007 using the trapezoidal rule (Turner, 2000).

Since the joint torque results in linear movement of joints, energy transfer through joints will occur, due to joint reaction forces. The corresponding power (P_{r}) can be calculated as the scalar product (Zatsiorsky, 2002):

$$P_{\text{r}} = \mathbf{F} \cdot \mathbf{v}, \tag{1}$$

where the three-dimensional vectors $\mathbf{F}$ is the joint reaction force and $\mathbf{v}$ is the linear velocity of the joint center. The term "joint force" denotes two forces according to Newtons third law: The action and reaction. Two adjacent segments exert two equal and opposite forces, $\mathbf{F}$ and $-\mathbf{F}$, on each other. The power of $\mathbf{F}$ is equal in magnitude and opposite in sign to the power of $-\mathbf{F}$, and so their sum is zero. As a consequence, the energy of one of the adjacent segments increases, while the energy of the other segment decreases by an equal amount. Hence, the total mechanical energy of the entire system does not change. The scenario is illustrated in Figure 3 B. Using the method of inverse dynamics, The AnyBody Modeling System computed the joint reaction force ($\mathbf{F}$) in the following joints: Glenohumeral, elbow, wrist and hand-racket joint. Power exchanged by reaction forces between the adjacent segments were calculated using equation (1) within The AnyBody Modeling System. To analyze the proximal-distal sequence, the time occurence of the peak joint powers were calculated.

Calculating the net change of energy in the segments, due to joint reaction forces, makes it possible to determine to what extent, the subjects are able to transfer energy from proximal to distal segments. Since this abilty is associated with a good technique, the following computations is of great interest. Let $P_{\text{r,gh}}$, $P_{\text{r,el}}$, $P_{\text{r,wr}}$ and $P_{\text{r,hr}}$ denote the joint powers of the joint forces at the glenohumeral, elbow, wrist and hand-racket joint, respectively. Then the net change of energy of the upper arm (E_{u}), in the period from t_1 to t_2, due to joint reaction forces is:

$$E_{\text{u}}\Big|_{t_1}^{t_2} = \int_{t_1}^{t_2} P_{\text{r,gh}} \, dt - \int_{t_1}^{t_2} P_{\text{r,el}} \, dt.$$

Similar computations are valid for the three remaining segments. Once again we used numeric integration to carry out these calculations. Subsequently, the maximal segment energies, due to joint reaction forces, were calculated to investigate the amount of energy transferred to the distal segments (forearm, hand and racket handle).

The reader should notice that the following nomenclature will be used: GH: Glenohumeral, EL: Elbow, WR: Wrist and HR: Hand-racket.

2.4 Statistical Analysis

The Student's t-test was applied for analyzing the differences between the two groups. This type of test is used for comparing mean values of two independent and normally distributed samples (Lee, 2004), which is the case in the present study. The test is also referred to as an unpaired test.

The standard statistical significance level of $\alpha = 0.05$ was chosen for testing the hypotheses. The t-test was carried out like a one- or two-tailed test, in accordance to the type of hypothesis. Only mean values regarding the hypotheses were tested. All tests were carried out using the statistical software `R` (The R Foundation For Statistical Computing, Wien, Austria).

3 Results

3.1 Forehand clear stroke

The mean racket head speed for the forehand clear stroke was calculated to 37.62 $\pm$ 3.3 m/s and 35.94 $\pm$ 2.4 m/s for groups A and B, respectively. No significant difference in racket head speed was found (p = 0.1047). For most of the trials the racket head reached peak speed just at the time of impact. The racket head showed great acceleration just before impact where the racket head speed went from around 10 m/s to its peak value in less than 0.1 seconds. These observations were obtained for both groups. Figure 4 illustrates the time-velocity graph and the position of the skeletal model on chosen time steps.

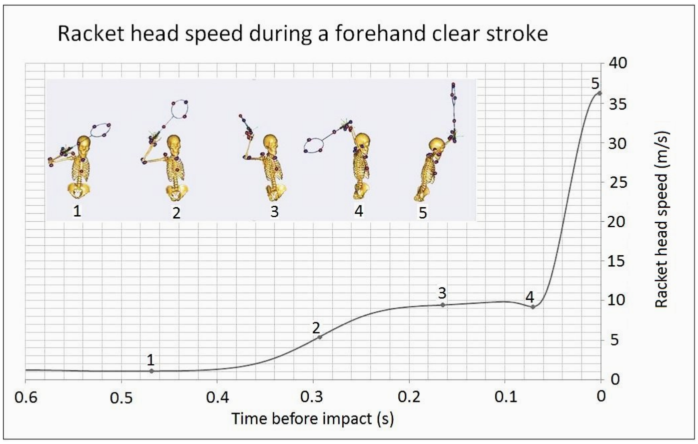


Figure 4: A typical example of the development of the racket head speed (m/s) during a forehand clear stroke. The stroke was performed by subject 9 from group A.

3.1.1 Kinematic analysis

The segment and joint angular velocities were succesfully obtained by The AnyBody Modeling System. An example of their development is shown in Figure 5. The results showed that the segment and joint movements leading up to impact was: Thorax lateral flexion (towards shuttle), thorax flexion, thorax longitudinal rotation (towards shuttle), glenohumeral internal rotation, glenohumeral abduction, glenohumeral flexion, elbow extension, elbow pronation, wrist flexion, wrist adduction and the relative movement between the hand and racket.

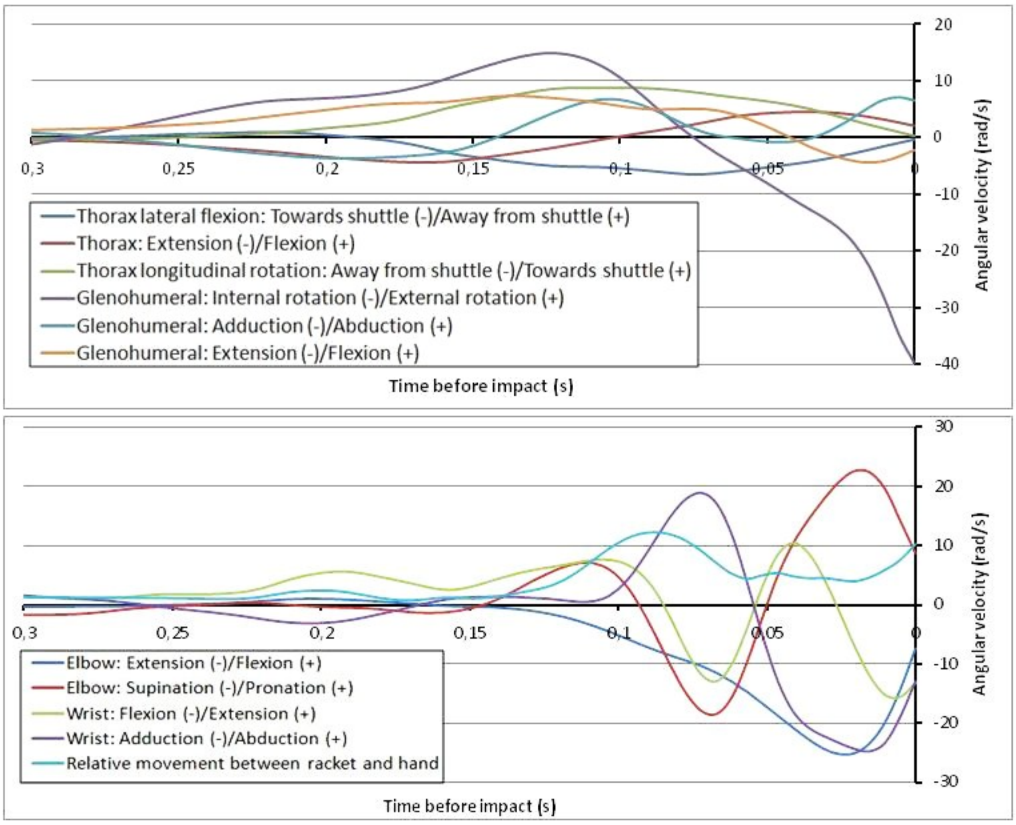


Figure 5: The segment and joint angular velocities (rad/s) in a forehand clear stroke performed by subject 1 from group A. The upper graph shows the thorax and glenohumeral joint movements, while the lower graph shows the elbow, wrist and hand-racket joint movements.

Figure 6 shows the time occurence of the maximal angular velocities for the segment and joint movements leading up to impact. It follows that both groups used the same coordination, where the late occurence of the glenohumeral internal rotation, elbow pronation and wrist flexion should be noticed. For group A, these joint movements attained their maximum at 0.003 s, 0.017 s and 0.006 s before impact, respectively. For group B, the results were similar with mean values of 0.005 s, 0.017 s and 0.012 s, thus no statistical significant differences were found ($p = 0.272$, $p = 0.464$ and $p = 0.229$).

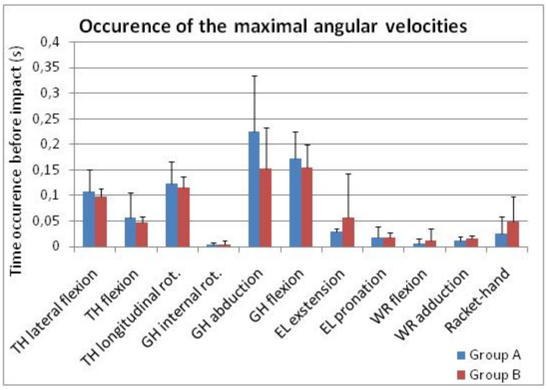


Figure 6: The time occurence of the maximal angular velocity of the segment and joint movements during a forehand clear stroke averaged over all subjects within the two groups. * Statistical significant difference with $p < 0.05$.

The maximal angular velocity of the glenohumeral internal rotation, elbow pronation and hand flexion was determined to 33.79 ± 12.7 m/s, 18.32 ± 6.76 m/s and 16.92 ± 6.47 m/s for group A, whereas group B reached mean values that were slightly lower. The hypotheses regarding these movements were tested and showed no significant differences ($p = 0.162$, $p = 0.410$ and $p = 0.285$). The mean values from the kinematic analysis are summarized in Table 2 and Table 3.

	TH lateral flex. (forward) (rad/s)	TH flexion (rad/s)	TH longitudinal rot. (forward) (rad/s)	GH flexion (rad/s)	GH abduction (rad/s)	GH internal rot. (rad/s)
Group A	7.45 ± 2.99	4.30 ± 1.64	9.41 ± 3.36	5.00 ± 2.50	7.26 ± 2.55	33.79 ± 12.7
Group B	6.72 ± 3.26	3.96 ± 1.34	8.04 ± 3.00	4.53 ± 2.14	7.24 ± 1.86	27.60 ± 9.21

Table 2: Mean values of the maximal angular velocities (rad/s) of the thorax and glenohumeral joint movements within the two groups. * Statistical significant difference with $p < 0.05$.

	EL extension (rad/s)	EL pronation (rad/s)	WR flexion (rad/s)	WR adduction (rad/s)	Relative hand-racket movement (rad/s)
Group A	21.09 ± 4.74	18.32 ± 6.76	16.92 ± 6.47	21.28 ± 5.45	12.05 ± 1.96
Group B	18.37 ± 4.24	17.68 ± 5.46	16.29 ± 4.57	20.59 ± 4.51	13.81 ± 7.01

Table 3: Mean values of the maximal angular velocities (rad/s) of the elbow, wrist and relative hand-racket joint movements within the two groups. * Statistical significant difference with $p < 0.05$.

3.1.2 Joint work and joint power

Looking at the joint work produced by the joint torques, no significant differences in the total absolute joint work were found. The total absolute joint work was calculated to 67.24 J and 58.60 J for groups A and B, respectively ($p = 0.842$). Hence, the analysis revealed slightly opposite results to those proposed in the hypothesis. The absolute joint work at the four joints are presented in Table 4, here it appears that no differences exists between the two groups.

	Absolute glenohumeral joint work (J)	Absolute elbow joint work (J)	Absolute wrist joint work (J)	Absolute hand-racket joint work (J)	Total absolute joint work (J)
Group A	41.20 ± 12.60	15.44 ± 8.10	10.00 ± 4.71	0.60 ± 0.26	67.24 ± 19.79
Group B	34.01 ± 9.80	17.44 ± 5.33	6.73 ± 1.84	0.42 ± 0.11	58.60 ± 14.71
p-value	0.906	0.256	0.971	0.974	0.842

Table 4: Mean values of the absolute joint work (J), from joint torques, produced at the glenohumeral, elbow, wrist and hand-racket joint in the two groups. * Statistical significant difference with $p < 0.05$.

With regards to the joint power produced by joint reaction forces, the time-power graphs of the four joints followed the same pattern for all subjects in group A and most of the subjects in group B. This is exemplified in Figure 7 A. The time-power graphs were divided into two phases. In phase 1 the time-power graphs showed a proximal-distal sequence where the joint powers attained peak values in the following order: Glenohumeral, elbow, wrist and hand-racket joint. In phase 2 negative energy transfer over the joints occured close to impact. Since the racket head keeps on accelerating at this time of the stroke (Figure 4), it seems that the deceleration of the hand causes a whiplash effect within the rigid racket body, as suggested by Rasmussen et. al. (2010).

As mentioned, some subjects in group B deviated from the coordination described above. Figure 7 B illustrates the time occurence of the maximal joint power, from reaction forces, in phase 1, where the deviations from the proximal-distal sequence is illustrated by the bigger standard deviation in group B. However, no statistical significant differences were found in the time occurence of the peak joint powers.

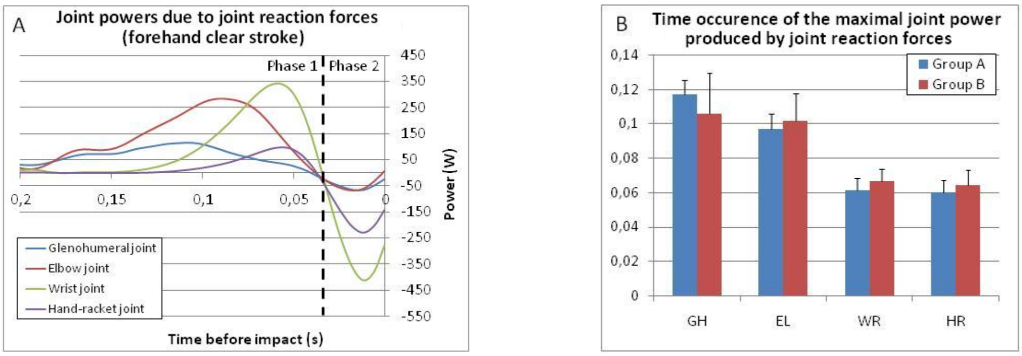
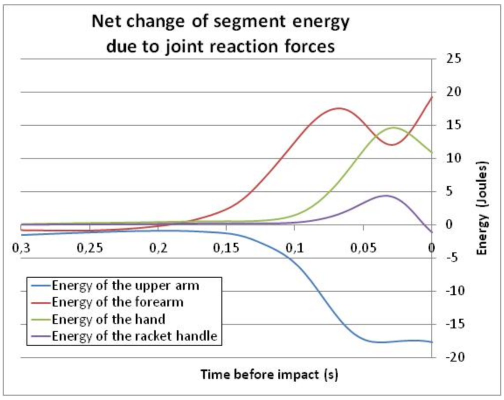


Figure 7: A) An example of how the joint power (W), from joint reaction forces, develops during a forehand clear stroke performed by subject 3 from group A. B) The time occurence of the maximal joint power from joint forces at the glenohumeral, elbow, wrist and hand-racket joint averaged over all subjects in the two groups. * Statistical significant difference with $p < 0.05$.

Figure 8 shows the net change of segment energy due to joint reaction forces. The loss of energy in the upper arm and the corresponding gain of energy in the forearm indicates a great flow of energy between these segments. These observations were valid for both groups. Mean values of the maximal energy in the forearm were 26.10 ± 10.15 J and 21.22 ± 4.78 J for groups A and B, respectively. Similar development occurred between the forearm and hand, where a loss of energy in the forearm led to a gain of energy in the hand. The results showed no significant difference in the maximal energy in any of the segments, as stated in Figure 8.



	Maximal segment energy (J) (Group A)	Maximal segment energy (J) (Group B)	p-value
Forearm	26.10 ± 10.15	21.22 ± 4.78	0.092
Hand	16.34 ± 3.93	14.76 ± 3.90	0.190
Racket handle	5.13 ± 1.27	4.49 ± 1.18	0.129

Figure 8: Left: Net change of segment energies (J), due to joint reaction forces, during the forehand clear stroke performed by subject 3 in group A. Right: The peak segment energies (J) due to joint reaction forces. * Statistical significant difference with $p < 0.05$.

3.2 Backhand clear stroke

The mean racket head speed at impact, for the backhand clear stroke, was calculated to 26.77 ± 8.57 m/s and 25.12 ± 9.53 m/s for groups A and B, respectively. No significant difference in the racket head speed was found (p = 0.090). However, there was a significant difference in the maximal racket head speed (p = 0.007). The calculated mean values were 30.77 ± 2.88 m/s and 27.03 ± 3.19 m/s for groups A and B, respectively.

As opposed to the forehand clear stroke the racket head reached peak velocity somewhat before impact for both groups. This is exemplified in Figure 9 which shows the time-velocity graph and the position of the skeletal model on certain time steps for two arbitrary chosen subjects from each group.

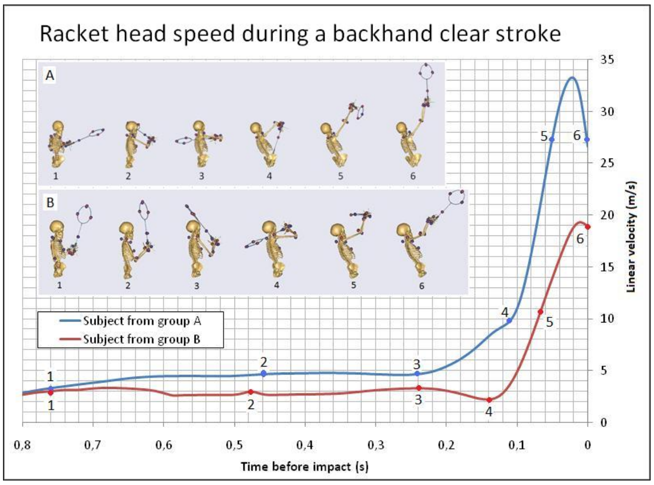


Figure 9: The time-velocity graph with appertaining images of the skeletal model during a backhand clear stroke. The strokes were performed by subject 9 from group A and subject 4 from group B.

3.2.1 Kinematic analysis

As Figure 9 indicates, the backhand clear stroke was executed differently between the two groups. The segment and joint movements were reasonably consistent within group A, and Figure 10 shows a typical behaviour of the angular velocities during the backhand clear stroke performed by a randomly chosen subject from this group.

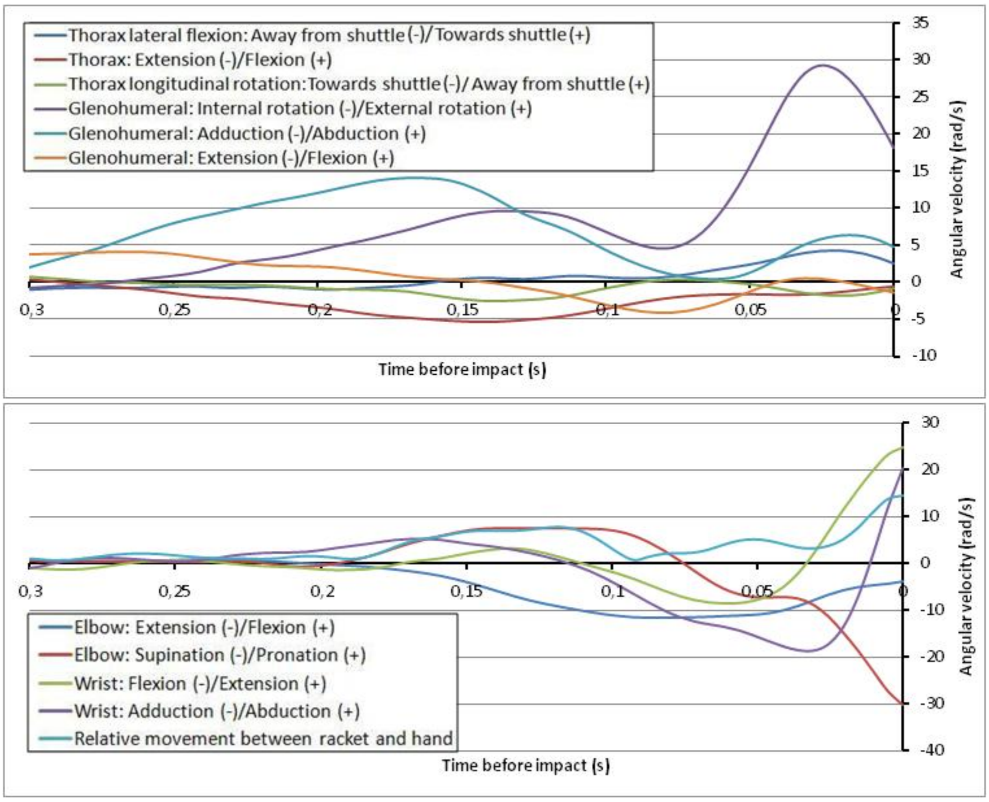


Figure 10: Segment and joint movements during a backhand clear stroke performed by subject 5 from group A.

The joint movements leading up to impact was: Thorax lateral flexion (towards shuttle), thorax extension, thorax longitudinal rotation (towards shuttle), glenohumeral external rotation, glenohumeral abduction, glenohumeral extension, elbow extension, elbow supination, wrist extension, wrist abduction and the relative hand-racket movement.

The coordination of the segment and joint movements were different between the two groups. Figure 11 shows the time occurence of the maximal angular velocity of the movements leading up to impact. With regards to the hypotheses significant differences were found in the time occurence of the glenohumeral external rotation and wrist extension (p = 0.049 and p = 0.036). For group A, both joint movements reached peak values closer to the time of impact where the glenohumeral external rotation and wrist extension attained their maximum at 0.042 s and 0.004 s before the time of impact. In contrary, the time occurences for group B were 0.105 s and 0.072 s. Regarding the elbow supination no significant difference was found, but one should notice the late time occurence.

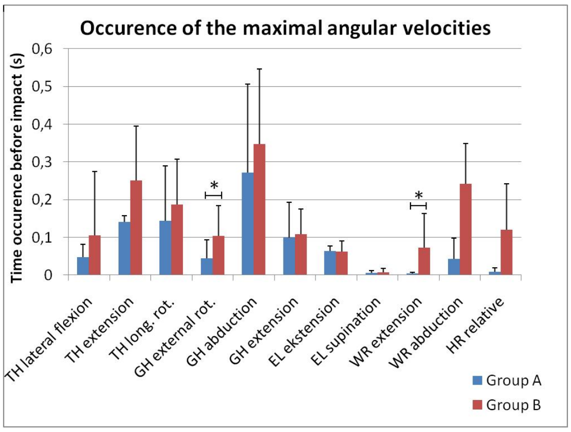


Figure 11: Time occurence of the maximal angular velocities of the segment and joint movements during the backhand clear stroke averaged over all subjects in groups A and B, respectively. * Statistical significant difference with $p < 0.05$.

Looking at the mean values of the maximal angular velocities, the results showed significantly higher angular velocities of the upper arm external rotation (p = 0.008), forearm supination (p = 0.028) and wrist extension (p = 0.0009). The angular velocity of the upper arm external rotation was calculated to 33.91 ± 7.76 rad/s for group A, whereas group B reached a mean value of 25.91 ± 7.74 rad/s. Regarding the elbow supination and wrist extension, the results are stated in Table 5 and Table 6.

	TH lateral flexion (rad/s)	TH extension (rad/s)	TH longitudinal rot. (rad/s)	GH extension (rad/s)	GH abduction (rad/s)	GH external rot. (rad/s))
Group A	3.38 ± 1.65	4.39 ± 1.58	3.25 ± 3.32	4.85 ± 1.93	16.00 ± 5.05	33.91 ± 14.23 *
Group B	4.47 ± 1.65	2.36 ± 1.96	4.24 ± 3.77	4.75 ± 1.44	17.50 ± 5.54	25.91 ± 17.32

Table 5: Mean values of the maximal angular velocities of the thorax and glenohumeral joint movements within the two groups. * Statistical significant difference with p < 0.05.

	EL extension (rad/s)	EL supination (rad/s)	WR extension (rad/s)	WR abduction (rad/s)	Relative hand-racket movement (rad/s)
Group A	13.00 ± 5.87	33.91 ± 14.23 *	24.71 ± 6.86 *	14.07 ± 4.50	12.53 ± 2.20
Group B	11.38 ± 7.66	25.90 ± 17.32	13.48 ± 6.52	6.91 ± 3.41	12.80 ± 2.76

Table 6: Mean values of the maximal angular velocities of the elbow, wrist and hand-racket joint movements within the two groups. * Statistical significant difference with p < 0.05.

3.2.2 Joint work and joint power

The calculated absolute joint work, from the joint torques, showed no support for the hypothesis stating that the work would be less for the skilled players. As a matter of fact the skilled players showed a greater absolute joint work at all four joints compared to the subjects in group B (Table 7).

	Absolute glenohumeral joint work (J)	Absolute elbow joint work (J)	Absolute wrist joint work (J)	Absolute hand-racket joint work (J)	Total absolute joint work (J)
Group A	46.20 ± 19.48	13.78 ± 3.98	10.83 ± 5.05	0.95 ± 0.34	71.76 ± 24.88
Group B	33.28 ± 15.26	9.99 ± 3.30	4.94 ± 2.67	0.64 ± 0.15	48.85 ± 19.38
p-value	0.942	0.984	0.998	0.992	0.982

Table 7: Mean values of the absolute joint work produced at the glenohumeral, elbow, wrist and hand-racket joint within the two groups. * Statistical significant difference with $p < 0.05$.

Focusing on the joint power and work produced by the joint reaction forces, distinct results were found between the two groups. With regards to the time-power graphs, all the skilled players showed a proximal-distal coordination in phase 1 (Figure 12 A), while most subjects within group B differed from this sequence in some way. The latter follows from the greater standard deviation and the distal-proximal sequence between the wrist and hand-racket joint, presented on Figure 12 B. A significant difference was found in the time occurence of the glenohumeral peak joint power from joint forces (p = 0.018). Mean values were 0.180 s and 0.269 s for groups A and B, respectively. No significant differences were found at the remaining joints. Looking at phase 2 the results were somewhat different from the forehand clear stroke, since the players produced positive joint powers just before impact. Possible explanations of this outcome will be discussed later on.

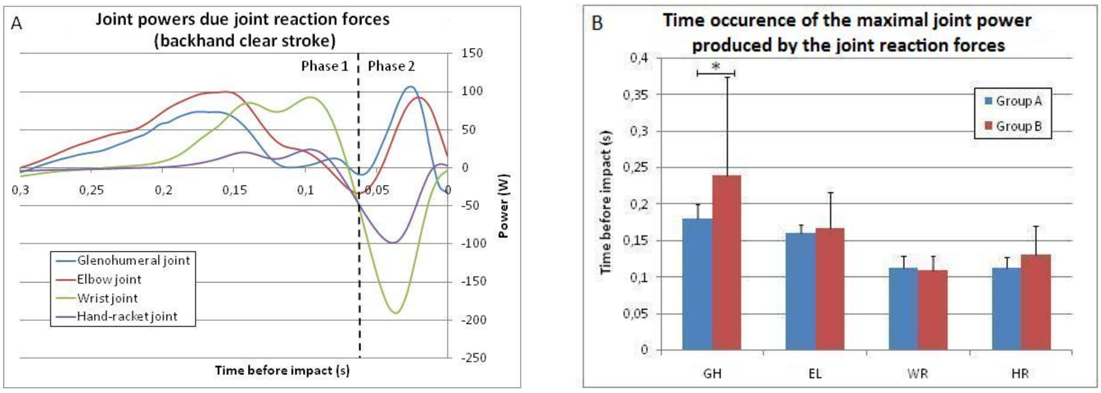


Figure 12: A) An example of how the joint power, from joint reaction forces, develops during the backhand clear stroke performed by subject 7 from group A. B) Time occurence of the maximal joint power, from joint forces, for the glenohumeral, elbow, wrist and hand-racket joint. * Statistical significant difference with $p < 0.05$.

The difference in coordination was clearly reflected in the net change of segment energies due to reaction forces. Figure 13 A shows how a skilled player lost energy in the upper arm but gained an equivalent amount of energy in the forearm. This pattern was valid for the interaction between the forearm and hand as well. In contrary, a less skilled player gained energy in the upper arm and lost a similar amount of energy in the forearm indicating a reverse energy transfer (Figure 13 B).

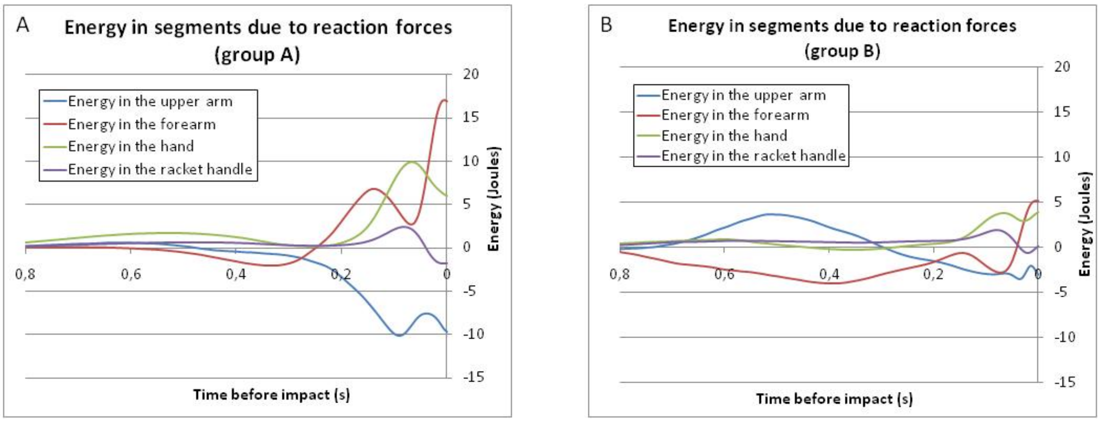


Figure 13: Net change of segment energies, due to joint reaction forces, for the backhand clear stroke performed by subject 3 from group A (A) and subject 2 from group B (B).

Table 8 shows that the peak segment energies, from joint reaction forces, in the forearm and hand were significantly higher for the skilled players. Especially the tremendous difference found in the forearm should be noticed. Mean values of 18.35 ± 7.80 J for group A, and 6.49 ± 4.85 J for group B, were obtained in this case (p = 0.0004).

	Maximal segment energy (J) - Group A	Maximal segment energy (J) - Group B	p-value
Forearm	18.35 ± 7.80	6.49 ± 4.85 *	0.0004
Hand	9.95 ± 2.91	7.56 ± 3.22 *	0.049
Racket handle	2.43 ± 0.60	1.99 ± 0.64	0.066

Table 8: The peak segment energies (J) of joint reaction forces. * Statistical significant difference with $p <$ 0.05.

4 Discussion

As mentioned in the introduction, the backhand clear stroke was considered a more complex skill compared to the forehand clear stroke which indeed was reflected in the obtained results. All together, it follows that the two groups executed the forehand clear stroke in much the same way, whereas the technique in the backhand clear stroke was quite different.

A racket head speed at around 36-37 m/s for the forehand clear stroke (valid for both groups) agree with earlier findings of 45-52 m/s for a smash (Liu et. al., 2002; Kwan et. al., 2010; Rasmussen et. al., 2010) taking the differences in anthropometric data and stroke type into account. As for the backhand clear stroke, the speed of 25-27 m/s showed a lower racket head speed compared to the forehand clear stroke, indicating a more complex movement.

As it follows from the obtained results all hypotheses, regarding the kinematic analysis for the forehand clear stroke, were rejected. Since the results to a high extent agree with earlier findings in similar throwing or hitting tasks executed by elite athletes, it seems that both groups performed a skilled movement. The timing of the maximal angular velocities of the segment and joint movements were much alike those found by Tillaar and Ettema (2009) in team handball despite the glenohumeral abduction movement, which attained its maximum closer to the time of impact. The longitudinal axis rotations of the upper arm and forearm reached peak values close to the time of impact as reported in a badminton smash (Liu et. al., 2002), a squash forehand drive and a tennis serve (Marshall and Elliott, 1999). These rotations did once again achieve the highest angular velocities compared to all other segment and joint movements, as stated in Table 2 and Table 3. They did, however, not reach values of 74 rad/s and 68 rad/s, as stated by Liu et. al. (2002), which again might be due to the difference in anthropometry and stroke type. The results supports the idea that such rotations may play a crucial role in producing high racket head speeds. The wrist flexion reached high angular velocities as well, yet they did not exceed the values found for the wrist adduction. The adduction/abduction and flexion/extension angular velocities were found to oscillate adversely during the stroke as illustrated in Figure 5. This behavior is consistent with the wrist working as a cardan joint which allows pronation of the forearm to be transmitted to hand rotation, despite the forearm and hand rotation axes having different orientations.

With regards to the backhand clear stroke the results showed a different picture. The later occurence of the maximal angular velocity of the glenohumeral external rotation and wrist extension found in group A, resembled the results found in the forehand stroke, thus indicating a skilled movement by this group. Furthermore, the three joint movements tested achieved the highest angular velocities of all joint movements and attained significantly higher values for group A (Table 5 and Table 6). Hence, these kinematic observations could lead to important areas of improvement for the less skilled players.

The hypotheses regarding the absolute joint work from joint torques were rejected. For the forehand clear stroke, the mean values were quite similar, whereas the skilled players attained higher mean values in the backhand stroke. The greater amount of absolute joint work found for the skilled players can possibly be explained by the stretch-shortening cycle of muscular contraction. When performing a skilled throwing or hitting task the segments often move in the opposite direction of the one intended. Such a countermovement is often necessary to allow the subsequent movement to occur, and as consequence beneficial phenomenas seem to emerge. For example principles like initiating the stretch reflex, storage of elastic energy and stretching the muscle to optimal length for a forceful contraction (Zatsiorsky, 2000). These principles could perhaps be considered a typical adaptation for skilled performers. Since the skilled players showed a greater range of motion for the majority of the segment and joint movements, this could indicate a greater use of the stretch-shortening cycle. If so, greater muscle torques would be generated creating a larger absolute joint work.

Even though no significant differences were found in the forehand clear stroke, there was a slight distinction in the timing of the peak joint powers, from joint reaction forces, between the glenohumeral joint and elbow joint (phase 1). Hence, some subjects from group B showed a simultaneous coordination, whereas two other subjects showed a distal-proximal sequence. This is indicated in Figure 7 B, where the time occurence of the glenohumeral and elbow joint power were quite similar and the standard deviations were somewhat greater compared to group A. However, these results did not lead to any differences in the net change of segment energy, due to joint reaction forces, though the peak segment energies were slightly higher for group A (Figure 8). Looking at two adjacent segments, the sudden loss of energy in the proximal segment and gain of energy in the distal segment, showed a great outward flow of energy. Both groups enabled such a transfer of energy from the thorax to the forearm, hand and racket handle. The joint powers, from joint reaction forces, did however not reach values of 1 kW over the wrist joint, as reported by Rasmussen et. al. (2010). In the present study the wrist joint power were calculated to 357 $\pm$ 107 W and 303 $\pm$ 108 W for groups A and B, respectively.

As regards to the backhand clear stroke, the differences in time occurence of the joint powers, from reaction forces, corresponds to the results obtained in the kinematic analysis, showing a difference in the coordination between the two groups. Both coordination measures showed much inconsistency in group B, thus making it difficult to clarify any general differences in coordination between the two groups. Some subjects showed a simultaneous timing of the glenohumeral and elbow joint power, while others showed a distal-proximal sequence. Furthermore, most subjects from group B showed a distal-proximal sequence with respect to the wrist and hand-racket joint. Such coordinations were clearly inappropriate, as it followed from the calculated peak segment energies (Table 8). Hence, the skilled players transferred significantly more energy from the proximal segments to the distal segments, due to joint reaction forces.

It is noteworthy how the joint powers, from the joint reaction forces, occurred in a proximal-distal sequence even though the maximal angular velocties of the segment and joint movements did not seem to follow the intuitive idea of such a coordination (Figure 6). Hereof, it seems that the proximal-distal sequence should be determined by analyzing the joint powers due to reaction forces, rather than looking at the maximal angular velocities of joint movements.

It is evident from the results obtained in the present study that it is a difficult task to state some general correction guidelines for the backhand clear stroke, hence each subject from group B had their very own style of execution. As an example subject 2 generated high angular velocities of the glenohumeral external rotation (26.5 rad/s), elbow supination (40.9 rad/s) and wrist extension (20.0 rad/s), and produced a large absolute joint work from the joint torques. He did, however, not succeed in producing high segment energies, from joint reaction forces, of which the peak values were 4.44 J, 3.82 J and 1.61 J for the forearm, hand and racket handle, respectively. As a result the maximal racket head speed of 26.23 m/s did not reach the same high values found in group A. In other words, it seems that subject 2 could improve his way of coordinating his limbs, thus creating af greater flow of energy due to reaction forces. Even though such a result is informative it can still be a challenging task for the coach to correct such an error. For other subjects the low angular velocities of the glenohumeral external rotation and elbow supination seemed to be the main reasons for the poor execution. It is expected that such an observation would be easier for the coach to implement, as the parameter is easier for the player to relate to. Overall, the present study did indeed provide important results that could lead to an improved technical performance by youth players.

During the experiment it was evident that both groups were able to execute the forehand clear stroke with an even higher speed. This would however make no practical sense, as the shuttle would fly past the opponents backline. In contrary, all subjects seem to execute the backhand clear stroke with maximal effort. In the light of this observation one should keep in mind that it is possible that differences between the two groups would occur, if the players executed a forehand stroke with the highest speed possible, as it is the case in a smash.

The quality of a stroke can be evaluated by different end parameters such as speed and accuracy. In the present study we solely investigated the speed of the stroke. Even though the racket head speed reached only slightly higher values in the backhand clear stroke for group A, it was obvious during the experiment that the less skilled players had considerably problems achieving accuracy in their execution. This is an interesting observation, yet none of the obtained data could confirm this. In future research it would however be of great interest to consider the accuracy of the stroke as well. Parameters of interest could be the racket head position at impact or the trajectory of the shuttle.

4.1 Stroke differences

As it follows from the above discussion both groups had less problems with achieving high racket head speeds in the forehand clear stroke compared to the backhand stroke. Hence, it is reasonably for one to ask what the reason for this might be. Comparing Table 4 and Table 7 it follows that the amount of absolute joint work, from joint torques, produced were relatively similar in the two strokes. Likewise, the maximal angular velocities of the longitudinal axis rotations were quite similar. In fact, the maximal angular velocities of the forearm longitudinal rotation were higher in the backhand stroke. On the other hand, there was a clear difference in the maximal segment energies, due to joint reaction forces (Figure 8 and Table 8). Hence, the difference between the two strokes appears to be embedded in the transfer of energy. There could be several reasons for that. Firstly, the maximal angular velocities of the thorax movements were quite smaller for the backhand clear stroke (Table 2 and Table 5). This difference could be a contributing factor to the reduced glenohumeral joint power of 75 W obtained in the backhand stroke, compared to the 172 W found in the forehand stroke (group A). Such an argument supports the general idea of the proximal-distal sequence, where large and heavy segments transfer energy to the subsequent lighter segments.

Secondly, the anatomical structure of the glenohumeral joint obviously sets limits for the upper arm movement during the backhand stroke. As a consequence, the glenohumeral joint did not move towards the shuttle, as it was the case for the forehand clear stroke. This was realised by drawing the linear velocity vector ($\mathbf{v}$) from equation (1), for the glenohumeral joint, and by calculating the corresponding vector length, within The AnyBody Modeling System. The behaviour of the vector was analyzed from the time the glenohumeral joint power, from the joint reaction forces, started to increase (Figure 14). From this analysis it followed that the vector length was smaller and the vector direction was different for the backhand clear stroke, compared to the forehand stroke. Similar calculations were carried out for the joint reaction force vector ($\mathbf{F}$) at the glenohumeral joint. Again, the results showed differences between the two strokes, as the vector length was clearly greater for the forehand clear stroke. Such a result makes sense since the anatomical structure of the shoulder girdle makes it possible for the scapula to exert great force on the humerus, when performing the forehand clear stroke. Even though the above-mentioned analysis was carried out on three trials only, the results were very consistent. Hence, these observations are most likely the reasons for the smaller glenohumeral joint power, from the joint reaction forces, found in the backhand stroke.

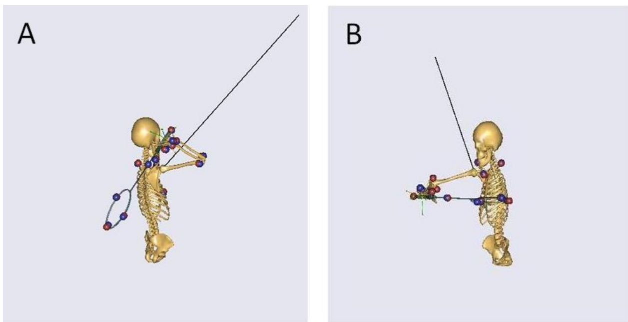


Figure 14: The linear velocity vector (black line) of the glenohumeral joint center in a forehand (A) and backhand clear stroke (B), executed by subject 10 from group A. Both images represent the time of which the glenohumeral joint power, from reaction forces, started to increase.

Furthermore, it appears that the anatomical structure was the reason for the different results found in the glenohumeral joint power, from joint reaction forces, in phase 2. Figure 15 shows the linear velocity vector and the joint reaction force vector at the glenohumeral joint, in the last frames before impact. As it follows from Figure 15, the velocity vector, for the two strokes, pointed in different directions, whereas the joint reaction forces showed the same development. Hence, for the backhand clear stroke the angle between the two vectors mostly stayed within $\pi/2$ radians, thus creating a positive glenohumeral joint power (see Figure 12 A), whereas the opposite situation was true for the forehand stroke (see Figure 7 A). Finally, the anatomical structure seem to be the reason for the loss of racket head speed in the backhand clear stroke just before impact, as illustrated on Figure 9.

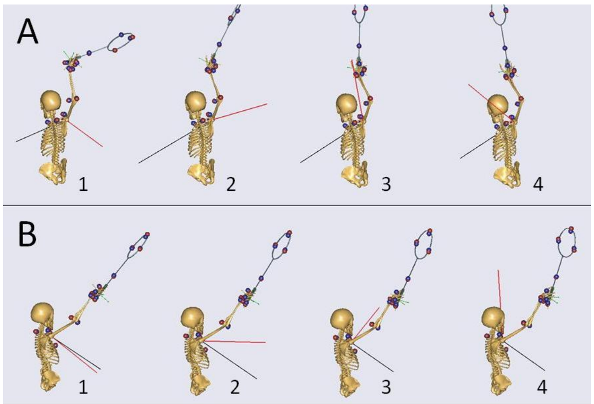


Figure 15: The linear velocity vector (black line) and the joint reaction force (red line) at the glenohumeral joint in a forehand (A) and backhand clear stroke (B), executed by subject 10 from group A. The numbers represent the order of the images, where image 4 denotes the time of impact. Notice, that the lengths of the vectors do not represent true values.

5 Conclusion

In conclusion, attention should be directed to the longitudinal axis rotations of the upper arm and forearm. Their high angular velocities and late time occurence, in all skilled movements, emphasize their unique part in the strokes. The wrist flexion/extension reached high angular velocities as well, and their oscillating behaviour, in the forehand stroke, have given additional information of the wrist joint function. We conclude that the skilled players reached significantly higher angular velocities of the glenohumeral external rotation, elbow supination and wrist extension in the backhand stroke. In contrary, no differences were found in the forehand stroke.

We conclude that the skilled players used a proximal-distal sequence, as regards to peak joint powers from joint reaction forces, in all strokes, thus transferring a great amount of energy to the distal segments. The less skilled players frequently deviated from this sequence, particularly in the backhand clear stroke. As a result, they did not transfer as much energy to the distal segments, in the backhand clear stroke, as it was the case for the skilled players. Finally, it seems that the skilled players, to a higher extent, utilize the stretch-shortening cycle, thus creating a greater joint work, from joint torques. However, further research is needed to make such a conclusion.

In closing, we emphasize that the coach should be aware of the presented differences between the two strokes. It is very likely that these differences have contributed to the lack of quality in the backhand clear stroke performed by the less skilled players.

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