Journal of Strength and Conditioning Research, 2007, 21(3), 950–957

Influence of Restricted Knee Motion During the Flat First Serve in Tennis

Olivier Girard,[1] Jean-Paul Micallef,[1,2] and Grégoire P. Millet[3]

[1]UPRES-EA 2991, Faculty of Sport Sciences, Montpellier, France; [2]INSERM ADR 08, Montpellier, France; [3]ASPIRE, Academy for Sports Excellence, Doha, Qatar.

Abstract. Girard, O., J.P. Micallef, and G.P. Millet. Influence of restricted knee motion during the flat first serve in tennis. *J. Strength Cond. Res. 21(3):950–957. 2007.*—The aim of this study was to examine the influence of restricted knee motion during the serve in tennis players of different performance levels. Thirty subjects distributed in 3 groups (beginner, B; intermediate, I; elite, E) performed 15 flat first serves with normal (normal serve, S_N) and restricted (restricted serve, S_R) knee motion. In S_R, the legs were kept outstretched by splints with a knee joint angle fixed at 10° (0° fully extended) to prevent any knee flexion/extension. Vertical maximum ground reaction forces (Fz_{max}), ball impact location (L_{impact}), and ball speed (S_{ball}) were measured with force platform, video analysis, and radar, respectively. Fz_{max}, $L_{impact,}$ and S_{ball} were higher ($p < 0.001$) in S_N than in S_R. S_{ball} was significantly ($p < 0.001$) dependent on performance level, with higher values recorded in E than in B or I. From S_R to S_N, increase in L_{impact} was greater ($p < 0.01$) in E than in other groups and increases in Fz_{max} and S_{ball} were correlated ($r = 0.69$, $p < 0.01$) in E only. Knee motion is a significant contributor to serving effectiveness whatever the performance level. Skilled players perform faster serves than their less skilled counterparts, and this is partly related to a more forceful lower limb drive.

Key Words. ball speed, biomechanics, ground reaction forces, performance, racquet sport, stretch-shortening cycle

Introduction

Modern tactics dictate that tennis players hit the ball both with maximal speed and with an acceptable level of control. In a tennis serve, an optimal racquet position, trajectory, height, and speed are necessary at the time of impact with the ball and are required to coordinate lower and upper body segments (6, 16). Ball speed and impact height have been presented as key variables underlying serving effectiveness (SE) in tennis (20, 25, 35).

By using 3-dimensional kinematic analysis to better understand the source of the joint torques exerted on individual body segments during the serve motion, previous studies have shown that the greatest contribution to forward velocity of the racquet head at impact was produced by the combined actions of internal rotation of the upper arm and wrist flexion (18, 37, 40). However, these results are debatable because Gordon and Dapena (21) recently questioned methods used in these studies to measure the contribution of the body segments motions to racquet speed at impact. They have shown that skin-attached markers could not be used to calculate accurately the upper arm twist, due to skin movement. For these authors, considering that the racquet speed at impact reflects only the conditions at this final instant of the process, the motions of some body parts, such as lower extremities occurring earlier in the serve sequence, are probably not important (21).

However, it is well known that the development of both linear and angular momentum starts with the ground reaction forces (GRF) generated by the players through their footwork (3). Recently, a technical model of the serve has been proposed to complement the subjective analysis of the shot by coaches (14). Several mechanisms underlying SE have been investigated by kinematics methods (17, 18, 39, 40) and discussed elsewhere (12, 13, 25). Proximal-to-distal sequencing has been clearly identified in the tennis serve (17, 37, 40). An essential aspect of this proximal-to-distal speed summation is that each segment movement is performed so that maximal speed is generated from the kinetic chain (23). The use of elastic energy and muscle preload both in the dominant arm/shoulder (4, 11) and in the leg muscles (20) was shown to be paramount for SE. An increase in the trajectory of the racquet during the forward swing is known to allocate time for the development of speed prior to impact (10, 11). Lesser is known about the lower extremity function, although GRF data (2, 16, 20, 30, 36, 41), kinematics of lower extremity (27), and relationships between lower body strength and ball speed (32, 35) have been reported.

The contributions of the different segments to the overarm throwing motion have been examined in various ways (28). One specific method approaching the problem of body segment contribution to sport performance is the joint immobilization or restraint paradigm. The theory justifying joints immobilization is based on a relatively simple process: the subject executes a given skill and the criterion of performance (i.e., height jumped or ball release) is recorded. The individual is then restrained in some way in an effort to eliminate or isolate the influence of movement in several or at a particular joint. Under these constraint conditions, the subject attempts to perform the original skill. Decrement in the value of the performance criterion is considered as a rough index of the role of the immobilized segments. Although this method has been largely employed in the field of sport biomechanics (i.e., baseball pitching [31] or overarm throwing [38]), it seems, however, not relevant to quantify or estimate numerically the contribution of individual joints to the final end point speed (28). Considering that the linking of forward (linear) and rotational (angular) motions is critical for the generation of racquet speed during the serve, one may argue that the removal of the use of lower extremities that constitute the starting point of the kinetic chain will necessarily affect service effectiveness through probable altered actions of the trunk or upper arm. In the present study, the use of the joint immobilization method could then be used as a paradigm for interrupting the normal mechanisms used by players to perform serves. Because most GRF studies have used skilled players, the role of the lower extremities in creating GRF across skill levels in the flat tennis serve remains unclear. Although Girard et al. (20) recently showed that elite players had higher vertical forces and a different neuromuscular temporal pattern in leg drive than their lower counterparts during serves, it is unknown whether the restriction of knee motion would differently affect players of various performance levels.

The aim of this study was therefore to examine the influence of restricted knee motion during the serve in tennis players of different performance levels. It was hypothesized that the restricted knee motion induces a greater decrease in service effectiveness in skilled players than in beginners.

Methods

Experimental Approach to the Problem

Subjects were tested in early April during a precompetitive period (1 month prior to the major individual championship in May). After a standardized warm-up lasting 10 minutes (i.e., submaximal run, knee extensions), subjects who where distributed into 3 experimental groups (beginner, intermediate, elite) according to their tennis performance level completed a set of 3 countermovement jumps (CMJs) from a force platform to evaluate peak lower extremity muscular power. Then they performed serves for an additional 10 minutes with increasing speed. After this, the subjects were asked to perform randomly sets of 15 flat first serves with normal (normal serve [S_N]) or restricted (restricted serve [S_R]) knee motion. To test the influence of restricted knee motion, the legs were kept outstretched in S_R by splints with a knee joint angle fixed at 10° (0° fully extended) to prevent any knee flexion/extension. All experiments were conducted on an outdoor Greenset tennis court.

Subjects

A group of thirty right-handed men (age: 21.3 ± 3.8 years; height: 179.7 ± 7.0 cm; body mass: 74.1 ± 9.8 kg) completed the study. Based on the international tennis number (ITN) equivalents established by the International Tennis Federation, participants were distributed into 3 experimental groups: (a) beginner (B; ITN 9, $N = 7$): tennis players with irregular practice in competitions but regularly physically active (sport recreation); (b) intermediate (I; ITN 5, $N = 10$): good club players who have played competitive tennis for many years; and (c) elite (E; ITN 2, $N = 15$): players of national level who regularly practice with high intensity. No significant differences in age, height, and weight were observed between the 3 groups. Mean training characteristics of subjects were years of practice, 9.1 ± 6.6 years (0.9 ± 0.1, 6.9 ± 3.8, and 14.9 ± 3.0 years in B, I, and E, respectively); technical/tactical training, 5.2 ± 4.6 h·wk^{-1} (1.2 ± 2.2, 5.7 ± 3.1, and 7.4 ± 4.8 h·wk^{-1} in B, I, and E, respectively); physical training, 3.6 ± 3.1 h·wk^{-1} (3.0 ± 4.3, 4.3 ± 2.9, and 3.5 ± 2.7 h·wk^{-1} in B, I, and E, respectively). The conditioning program of the 3 groups focused mainly on aerobic and anaerobic capabilities enhancement and included general cardiovascular exercises (i.e., long distance running [30–40 minutes], short [10, 20, 40 m], and long [100, 200, and 400 m] interval training). Additionally, subjects performed a variety of plyometric (i.e., medicine balls, hopping) and resistance training modalities

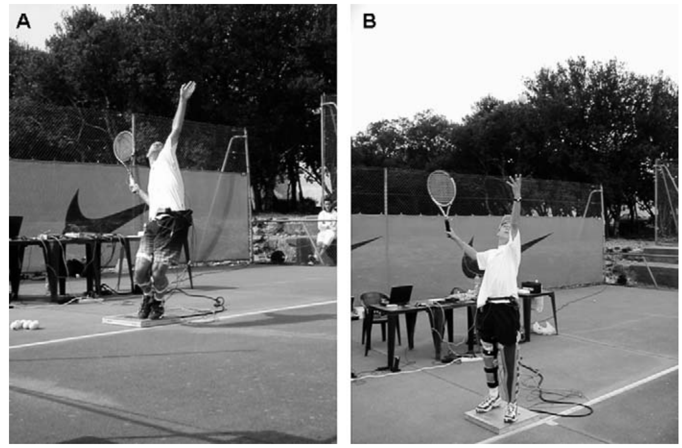

Figure 1. Example of a subject performing tennis flat first serves with normal (A) and restricted (B) knee motion. During tennis serves with restricted knee motion, the legs were kept outstretched by splints with a knee joint angle fixed at 10° to prevent any knee flexion/extension.

(i.e., variable resistance, isokinetics, free weights, or rubber tubing) in order to build a good strength base. In I and E, the conditioning training was periodized with cycles of 4 weeks. This method has been shown to be efficient to enhance serve velocity in advanced players (24). Informed consent was given by all the subjects, and a local ethics committee for the protection of individuals gave their approval to the project before its initiation.

Procedures

Vertical Jump Testing. During CMJ subjects started from an erect standing position and made a downward movement before starting to push off vertically in one continuous movement (no pause). Subjects were asked to keep their hands on their hips. The force platform measurements were used to calculate peak lower extremity muscular power (W·kg^{-1}) of the center of mass as the product of vertical component of GRF (Fz, N) and vertical velocity (Vv, m·s^{-1}) (9). Based on the force-time principle (Newton's second law of motion), V_v was calculated by integrating the force-time curve of Fz (vertical acceleration) from the beginning of the concentric (propulsive) phase. Subjects were asked to jump as high as they could 3 times, and the best performance was reported. Coefficient of variation was calculated for peak lower extremity muscular power (CMJ) as the ratio of standard deviation by the mean and averaged 5.5 ± 3.8%.

Serving Tests. The experiment consisted of flat first serves performed both with S_N and S_R knee motion (Figure 1). All serve trials were completed from the deuce or right service court with a 30-second rest between trials until 15 acceptable serves were accomplished. An acceptable serve required the ball to be hit with maximum speed relative to the ability of the player (from the judgement of a professional coach) and land in the ad-side service area. During S_N, subjects were asked to perform flat first serves as used in official competition. In S_R, the legs were kept outstretched by splints (Macrimed, Medical supplies, Paese, Italia) with a knee joint angle fixed at 10° (0° fully extended) to prevent any knee flexion/extension. Thus, only trunk and upper-limb segments were used to perform serves.

Force Platform Recordings. A force platform (Captels

TABLE 1. Performance parameters during the flat first serve performed with restricted (restricted serve [S_R]) and normal (normal serve [S_N]) knee motion for the 3 performance level groups.*

	S_R			S_N		
	B (n = 7)	I (n = 10)	E (n = 13)	B (n = 7)	I (n = 10)	E (n = 13)
S_{ball} (km/h)	89.1 ± 4.9	126.6 ± 6.8	144.6 ± 14.1	107.2 ± 6.1	148.8 ± 16.3†	169.4 ± 11.3†‡
L_{impact} (cm)	78.8 ± 3.5	82.1 ± 5.7	81.4 ± 3.8	81.7 ± 3.7	86.9 ± 5.3	87.9 ± 4.0§
H_{impact} (%)	144.4 ± 5.7	146.3 ± 5.4	145.3 ± 3.9	145.9 ± 7.2	148.4 ± 5.4	147.5 ± 3.8

* Values are mean ± *SD*. B = beginner group; I = intermediate group; E = elite group; S_{ball} = postimpact ball speed; H_{impact} = impact height; L_{impact} = ball impact location. H_{impact} was normalized to the standing height of the subject. L_{impact} was determined as the difference between height of the racquet at impact and subject's standing height.
† $p < 0.001$; significantly different from beginner group.
‡ $p < 0.05$; significantly different from intermediate group.
§ $p < 0.05$; significantly different from beginner group in S_N.

SA, Saint Mathieu de Treviers, France) was used to monitor Fx, Fy, and Fz orthogonal components of the GRF. The force platform used was 50 × 50 cm and surrounded by a raised wooden surface area. For each trial, 3 components of forces were sampled at 500 Hz simultaneously by using an analog-to-digital convertor (MP 100A-CE; Biopac, Santa Barbara, CA). In the present study, all subjects replicated their own specific stance position.

Video and Radar Recordings. Postimpact ball speed (S_{ball}, km·h^{-1}) was measured for each trial by the means of a radar (Stalker ATS, Plano, TX) fixed on a 2.5-meter height tripod, 2 meters behind the players in the direction of the serve. The racquet-ball impact height (H_{impact}, cm) was measured by a video camera (JVC, Ottawa, Ontario, Canada), operating at 50 Hz, located laterally on a rigid tripod behind a 3-meter guide mark made of 2 metallic poles connected with colored yarns vertically every 10 cm. From the tapes, a researcher visually estimated H_{impact} with a precision of ± 1 cm. The reliability of this way of measuring H_{impact} was assessed by the same experimenter digitizing 10 successful randomized trials on 3 different days and was satisfying (coefficient of variation = 0.7 ± 0.3%).

Analysis and Treatment of Data

Both for S_N and S_R, the 10 trials with the highest S_{ball} were used for subsequent analysis. Vertical maximum GRF (Fz_{max}) was normalized to body weight and H_{impact} to the standing height of the subject (H_{impact}, %). Ball impact location (L_{impact}, cm) was determined as the difference between height of the racquet at impact and subject's standing height. For each trial, minimal and maximal values for the 3 GRF components during the serve were identified using Acqknowledge software (3.7.2, Biopac, Santa Barbara, CA). For analysis purposes, GRF were expressed as difference (Δ) between maximal and minimal values. Serving effectiveness was evaluated through performance parameters including S_{ball}, H_{impact}, and L_{impact}. Changes between the 2 serve conditions were also calculated for performance parameters (S_{ball}, H_{impact}, and L_{impact}) and kinetic variables (Fz_{max}, ΔFx, ΔFy, and ΔFz). Intertrial variability (coefficient of variation) of dependent variables, i.e. kinetic variables (5.1 vs. 4.6, 12.0 vs. 10.1, 11.7 vs. 12.4, and 9.6 vs. 11.1% for Fz_{max}, ΔFx, ΔFy, and ΔFz) and performance parameters (7.0 vs. 7.6, 2.2 vs. 2.4 and 0.6 vs. 0.7% for S_{ball}, H_{impact}, and L_{impact}), was not different in S_N and S_R, respectively.

Statistical Analyses

Means and standard deviations were calculated for all variables. The normality of the distribution of each variable was tested by the Kolmogorov–Smirnov test. When the normality condition was accepted, a one-way analysis of variance (ANOVA) was used to test the effect of performance level on peak lower extremity muscular power and percentage of variation from S_R to S_N in kinetic variables and performance parameters. The effect of performance level on type of serve was verified by a 2-way ANOVA with repeated measures (3 groups [B, I, E] × 2 conditions [S_R vs. S_N]) on kinetic variables (Fz_{max}, ΔFx, ΔFy, and ΔFz) and performance parameters (S_{ball}, H_{impact}, and L_{impact}). This analysis showed the global effect of the type of serve, the global effect of performance level and, the effect of interactions between type of serve and performance level conditions. When significant main effects were observed with the 2-way ANOVA, Bonferroni posthoc analyses were used to identify differences among means. Pearson correlation coefficient was used to assess the relationships between changes in selected GRF data and performance parameters between the 2 serve conditions in each performance level group. The level of significance was established at $p \leq 0.05$ for all procedures (SigmaStat 2.3, Jandel Corporation, San Rafael, CA).

RESULTS

Vertical Jump Ability

No statistically significant difference (F_1 = 1.1; p = 0.36) in peak lower extremity muscular power (59.5 ± 10.1, 61.2 ± 5.9, and 63.8 ± 5.5 W·kg^{-1} in B, I, and E, respectively) was observed between groups.

Performance Parameters

Performance parameters (S_{ball}, H_{impact}, and L_{impact}) data in the 2 serve conditions for each performance level group are displayed in Table 1. There was a significant effect of type of serve on V_{ball} ($F_{1,6}$ = 101.9; $p < 0.001$). No significant interaction effect between type of serve and performance level ($F_{2,12}$ = 0.8; p = 0.468) was found in S_{ball}, but there is a significant performance level effect ($F_{2,12}$ = 69.8; $p < 0.001$): posthoc analysis showed a higher V_{ball} in E than in B ($p < 0.001$) or I ($p < 0.05$) but also in I than in B ($p < 0.001$). There was a significant increase ($F_{1,6}$ = 47.8; $p < 0.001$) in H_{impact} from S_R to S_N, but there was no significant difference in H_{impact} between groups ($F_{2,12}$ = 0.4; p = 0.68), nor any significant interaction ($F_{2,12}$ = 1.5; p = 0.26). There was a significant increase ($F_{1,6}$ = 249.1; $p < 0.001$) in L_{impact} from S_R to S_N, and this increase tended ($F_{2,12}$ = 2.5; p = 0.06) to be dependent on performance level. L_{impact} displayed a significant interaction effect ($F_{2,12}$ = 8.4; $p < 0.01$) between type of serve and performance level. This interaction effect was due to a significantly

TABLE 2. Percentage of variation in kinetic and performance parameters variables from the restricted (restricted serve [S_R]) to the normal serve (normal serve [S_N]) conditions for the 3 performance level groups.*

	B (n = 7)	I (n = 10)	E (n = 13)
S_{ball}	+16.9 ± 6.9	+15.1 ± 8.8	+14.8 ± 4.2
L_{impact}	+3.5 ± 2.6	+5.6 ± 2.0	+7.4 ± 1.7†‡
H_{impact}	+1.0 ± 1.3	+1.4 ± 0.7	+1.5 ± 1.0
ΔFx	+19.5 ± 20.6	+22.9 ± 37.0	+24.8 ± 20.0
ΔFy	+50.2 ± 10.9	+48.9 ± 33.3	+63.4 ± 17.3
ΔFz	+48.2 ± 27.4	+55.1 ± 18.8	+59.3 ± 10.6
Fz_{max}	+25.5 ± 14.6	+28.0 ± 11.9	+34.0 ± 11.2

* Values are mean ± *SD*. B = beginner group; I = intermediate group; E = elite group; S_{ball} = postimpact ball speed; H_{impact} = impact height; L_{impact} = ball impact location. H_{impact} was normalized to the standing height of the subject. L_{impact} was determined as the difference between height of the racquet at impact and subject's standing height. All components of forces are expressed as difference between maximal and minimal values (Δ) during the serve. GRF = ground reaction forces in the mediolateral (Fx), anteroposterior (Fy), and vertical (Fz) components.

† $p < 0.001$; significantly different from beginner group.

‡ $p < 0.05$; significantly different from intermediate group.

higher ($p < 0.05$) L_{impact} in E than in B in S_N only. Table 2 summarizes the percentage variations in performance parameters and kinetic variables for the 3 groups.

Kinetic Variables

Typical curves of GRF signals in the Fx, Fy, and Fz components of successful performance of a beginner and elite player during the 2 serve conditions are shown in Figure 2. Changes in kinetic variables, that is ΔFx ($F_{1,6}$ = 10.7; $p < 0.05$), ΔFy ($F_{1,6}$ = 44.2; $p < 0.001$), and ΔFz ($F_{1,6}$ = 62.6; $p < 0.001$), were higher in S_N than in S_R (Table 3). There was a significant effect of performance level on ΔFx ($F_{2,12}$ = 5.2; $p < 0.05$): posthoc analysis showed a smaller ΔFx in B than in E ($p < 0.05$) but only a tendency when compared with I (p = 0.06). The ΔFy ($F_{2,12}$ = 1.6; p = 0.24) and ΔFz ($F_{2,12}$ = 2.1; p = 0.17) were not significantly influenced by the performance level. The interaction of type of serve and performance level conditions was significant ($F_{2,12}$ = 3.8; $p < 0.05$) in ΔFy. This interaction effect was due to a significantly higher ($p < 0.05$) ΔFy in E than in B in S_N only. Fz_{max} was significantly higher ($F_{1,6}$ = 54.3; $p < 0.001$) in S_N than in S_R, independently of performance level (Figure 3). There was no significant interaction between these 2 factors.

Relationships Between Kinetic and Performance Parameters

The relationship between increase in Fz_{max} and increase in S_{ball} from S_R to S_N in E is presented in Figure 4. Finally,

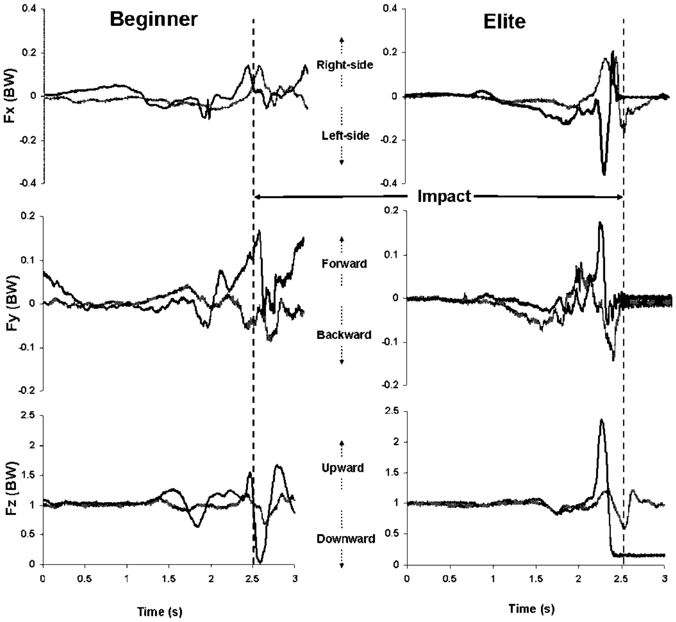

FIGURE 2. Typical curves of ground reaction forces signals in the mediolateral (Fx), anteroposterior (Fy), and vertical (Fz) components during a flat first serve performed with restricted (restricted serve, shaded line) and normal (normal serve, solid line) knee motion in beginner and elite players. Broken lines correspond to the time of racquet ball impact.

no significant correlations existed between changes in kinetic variables and in performance parameters between the 2 serve conditions in B and I.

DISCUSSION

This study examined the influence of restricted knee motion during the serve in tennis players of different performance levels. First of all, it is of the highest interest for the purpose of the present study to note that peak lower extremity muscular power was similar in the 3 groups. This suggests that the differences in kinetic variables observed during the serve were primarily due to technical/coordination aspects that characterize the different levels of expertise of the subjects.

To evaluate the influence of restricted knee motion during the tennis serve, the joint immobilization approach has been employed (28). Subjects attempted to perform flat first serves with normal and restricted knee motion, and decrement in the value of performance parameters and kinetic variables from the original (S_N) to the restraint condition (S_R) was recorded. This method was previously used in overarm throwing (28) and/or

TABLE 3. Peak ground reaction forces (BW) during the flat first serve performed with restricted (restricted serve [S_R]) and normal (normal serve [S_N]) knee motion for the three performance level groups.*

	S_R			S_N		
GRF (BW)	B (n = 7)	I (n = 10)	E (n = 13)	B (n = 7)	I (n = 10)	E (n = 13)
ΔFx	0.19 ± 0.04	0.23 ± 0.06	0.28 ± 0.08	0.25 ± 0.04	0.36 ± 0.15	0.39 ± 0.10†
ΔFy	0.11 ± 0.02	0.10 ± 0.04	0.09 ± 0.03	0.22 ± 0.05	0.24 ± 0.07	0.28 ± 0.00‡
ΔFz	0.47 ± 0.17	0.54 ± 0.16	0.58 ± 0.11	1.00 ± 0.34	1.27 ± 0.30	1.46 ± 0.30

* Values are mean ± *SD*. All components of forces are expressed as difference between maximal and minimal values (Δ) during the serve. B = beginner group; I = intermediate group; E = elite group; GRF = ground reaction forces in the mediolateral (Fx), anteroposterior (Fy), and vertical (Fz) components.

† $p < 0.05$; significantly different from beginner group.

‡ $p < 0.05$; significantly different from beginner group in S_N.

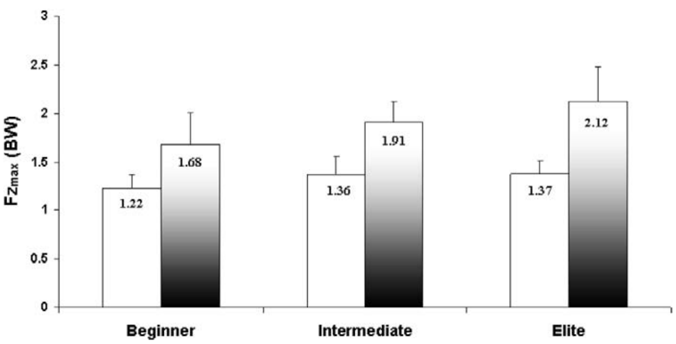

FIGURE 3. Vertical maximum component of ground reaction forces (Fz_{max}) during the flat first serve performed with restricted (restricted serve, white bar) and normal (normal serve, shaded bar) knee motion for the 3 performance level groups. Values are mean ± *SD*.

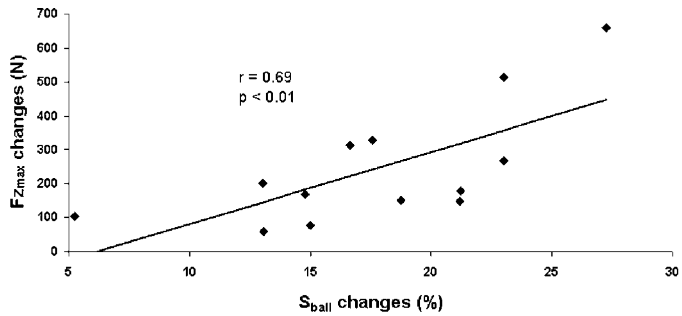

FIGURE 4. Relationship ($r = 0.69$, $p < 0.01$) between changes in vertical maximum component of ground reaction forces (Fz_{max} changes, N) and in postimpact ball speed (S_{ball} changes, %) during the flat first serve performed with restricted (restricted serve, S_R) and normal (normal serve, S_N) knee motion in elite players ($n = 13$). Fz_{max} is expressed without weight of the subject on the force plate.

jumping (26) to evaluate the influence of a particular joint or joints sequence to performance. Although physical immobilization of joints may provide some general insights into segmental contributions to performance, it is important to note that the restriction of one or more joints can also deteriorate the coordinated action of the other body segments (28). This may be particularly true for the tennis serve in which a number of body segments are coordinated in a sequence referred to as the kinetic chain (17, 23). Therefore, it seems clear that this approach, although used in the past, is inadequate to evaluate the contribution of a particular joint to the final outcome of a tennis serve. A valuable method of approaching the problem of the contributions of the different body segments and joints to the final velocity of the racquet head would be to focus on the resultant muscle torque patterns, which involves detailed computations of the internal forces responsible for ball speed (28). The influence of restricted knee motion, in the present study, was then used as a paradigm for interrupting the normal mechanisms used by players to perform the serve, rather than to focus on the contribution of lower limbs.

In the present study, the mean S_{ball} values measured in the traditional serve condition in the 3 performance level groups (107, 148, and 169 km·h^{-1} in B, I, and E, respectively) are in line with previous results in unskilled (87–108 km·h^{-1} [1, 29]) and national level (145–180 km·h^{-1} [5, 17, 19]) players. The range of H_{impact} values (144–149% of standing height) compares with previous findings (141–152%) in players of similar standard (5, 17), the greatest values being recorded in the more skilled players as a result of a forceful leg drive (20).

Although the reduced dimensions of the force plate might have limited force production, vertical GRF measured during the traditional serve condition in the present study (1.68–2.12 BW) are in accordance with those previously described (2, 19, 30, 41). Negligible mediolateral, low anteroposterior, and peak vertical force of one-third body weight were recorded in a study by Van Gheluwe and Hebbelinck (41). These peak vertical forces were lower than those reported elsewhere, in which players were able to generate considerable vertical forces (twice their body weight) with both foot-up (the rear foot is moved forward next to the front one during the "push-off" phase) and foot-back (the feet stay at the same relative level) stances (2, 19). The discrepancies are largely the result of the performance level of the players tested in the different studies. The development of linear momentum in the vertical and horizontal directions depends on the type of stance adopted by the player (2, 19). However, no difference in ball speed has been reported between the 2 stances (17) . In the present study, all beginner and intermediate and most of the elite players used a stance close to "foot-back," which is known to produce smaller vertical GRF but greater peak forward propulsive force, with the back leg favoring rapid displacement to the net (2, 19).

As expected, from the restricted to the traditional serve condition, significant increases in performance parameters and kinetic variables were recorded (Table 2), irrespective of the subject's expertise level. This indicates that, as required by the experimental design, the influence of knee motion was effectively minimized by the use of splints. This result confirms that knee motion is a significant contributor to serving effectiveness, whatever the performance level.

Elliott (10) has shown that a rhythmical action is the key to an effective serve. Several body segments have to be coordinated for producing a high-speed serve with an acceptable level of control, in a proximal-to-distal time sequence (13, 16, 17). In this sequence, the acceleration of the racquet through the ball is built up through the summation of the individual segments speeds, transferring linear and angular momentum generated from the GRF to the racquet (10, 23). In the present study, the larger GRF values (i.e. ΔFx, ΔFy, and ΔFz) in the normal condition are the result of a forceful leg drive. This suggests that lower extremities require some degree of knee flexion during the backswing to generate large amounts of linear and angular momentum during the knee extension, transferring the GRF to the trunk (3, 18). This consideration is also supported by previous studies hypothesizing that the largest portions (> 50%) of kinetic energy or force generated during the serve in world-class players are developed in the legs and trunk (22, 34). In the present study, only 1 force platform was used to determine GRF, which did not allow the accurate appreciation of the role of individual leg segments. However, it has been previously reported that the back leg provides most of the upward and forward push, whereas the front leg provides the stable post for the rotational momentum (3). It should be therefore assumed that the combined action of the lower extremities enhances the ability to generate trunk and upper-arm rotations later in the action, which in turn may contribute to enhanced SE (S_{ball}, $H_{impact,}$ and L_{impact}) from S_R to S_N.

Given that the changes in the total angular momentum of the body around the center of mass are primarily the result of the magnitude and direction of the reaction forces from the court (3, 17), one may argue that limiting leg movement has some effects not only on force production capabilities from GRF but also on ball toss, trunk, and hitting arm motions. In the serve, the trunk movement is a fundamental link in the kinetic chain that transfers energy from the extension of the lower limbs to the arm during the forward swing (3). As a consequence, one may speculate that the expected decrease in trunk angular momentum in the restricted knee flexion condition may have in turn decreased the ability of the shoulder to rotate rapidly internally, an action known to be a key factor in SE (18, 37).

Efficient kinetic chain force production for the serve requires commonalities in the sequence, including the use of elastic energy and muscle preload (11, 13, 20). As shown recently (20), lower-limb activity during the serve is characterized by a stretch-shortening cycle action, that is, an eccentric contraction (knee flexion) followed by a concentric one (knee extension). Without knee bend during S_R, quadriceps muscles were not stretched and therefore elastic energy was not stored in elastic components. As a consequence, it should be assumed that speed of leg extension was certainly near 0 at the beginning of the kinetic chain force production and that the role of the trunk was then limited.

It is well known that the legs require some degree of knee flexion during the preparation phase not only to decrease the loading in upper limbs segments (10) but also to assist players in driving the racquet down, behind, and away from the back (putting shoulder muscles on stretch [4]) and increasing the trajectory of the racquet prior to impact (17). It should therefore be assumed that the action of the lower extremities enhances the trunk and upper-arm rotations and facilitates the downward racquet motion. Although the type of backswing was shown to have minimal influence on service performance or on loading of the shoulder and elbow joints (10), it is of interest to note that when leg participation was allowed, greater values in kinetic variables (i.e., ΔFy, ΔFz, Fz_{max}) were recorded in the 3 groups of various expertise levels. For the flat and slice serves, Bahamonde (4) has shown that leg drive and trunk rotations produce a forced external (away from the direction of the serve) rotation of the upper arm, resulting in the stretch of the internal rotators muscles. On movement reversal, these stretched muscles are creating a higher speed of rotation of the hitting arm and consequently a higher postimpact ball speed (13). This phenomenon was certainly present during the traditional serve condition to accelerate the upper-arm segments and as a consequence the ball. Research has shown that 10 to 20% additional speed is achieved after a stretch-shortening cycle (11, 15). However, the ability to store elastic energy is affected by numerous factors, such as the level of preactivation, the muscle stiffness and compliance, the velocity and magnitude of stretch, and the coupling time between eccentric and concentric phases (42). In this context, one may argue that the storage of elastic energy and muscle preload were inevitably reduced during S_R as a result of the limited motions of the lower extremities and trunk. Restricting leg drive may have also altered the ideal positioning of trunk and upper-arm segments and therefore the rotation amplitude.

Although the present results confirm that the knee flexion before extension is a prerequisite for an efficient execution of the serve, it is important to note that the influence of restricted knee motion on performance parameters and kinetic variables was in part dependent on the performance level of the players. Although it is well documented that (a) weight distribution (center of pressure of GRFs) in the starting position is an individual characteristic (36) and (b) different stances produce different patterns of GRF curves (2, 19), one may argue that changes in magnitude of kinetic variables from S_R to S_N between players of various abilities primarily result in a more or less efficient leg drive, leading to different levels of SE.

An effective serve is characterized by vertical forces that induce the body to be driven off the ground for impact (2, 19, 41). This point is clearly supported by the vertical force curve in E (Figure 2). Again, Payne (30) reported that the angular momentum developed during the serve is the result of the vertical forces generating an off-center impulse behind the center of mass of the player, which helps to rotate the trunk forward (flexion, shoulder-over-shoulder, and rotation) in preparation for impact. This is confirmed by the fact that skilled players increased to a greater extent ball impact location from the restricted to the normal knee flexion condition than their lower counterparts.

Surprisingly, the decrease in S_{ball} from S_N to S_R was to the same extent in all groups (Table 2), although skilled players displayed higher S_{ball} values than their less skilled counterparts (Table 1). A possible explanation about the difference in the restricted serve condition could be the development of higher muscular forces in the dominant arm in skilled players, because measures of upper extremity's flexibility and muscular strength were found to be linked to postimpact ball speed during serves performed by elite performers (8).

It is interesting to note that from the restricted to the normal knee flexion condition, increase in Fz_{max} accounted for 48% of the variance of increase in S_{ball} in the highest skilled players only. This finding emphasizes that a forceful lower-limb drive is used to improve SE in skilled players (20, 27). Bartlett et al. (5) added further support to the relationship between leg drive and SE in skilled players by demonstrating that the difference in ball speed at impact between British national and county players was to a great extent the result of the timing of the movement of the back-foot forward during the preparation phase. Another interesting result is the greater increase in ΔFy from S_R to S_N in skilled players than in their less skilled counterparts. So the highest skilled players, producing a greater shift of the center of mass forward (36), are able to generate greater somersault (forward) angular momentum, which is a well-known factor contributing to the development of racquet and ball linear velocities at impact (3). Inversely, incorrect timing in the leg muscles activation and smaller magnitudes of GRF have been identified in unskilled players. It was suggested that kinetic chain breakage occurs in beginners who use compensative mechanisms to stabilize body segments in an attempt to hit the ball (20, 23). In the present study, these findings are supported by the lack of correlation between kinetic variables and performance parameters in unskilled individuals.

CONCLUSIONS

This study examined the influence of restricted knee motion during the serve in tennis players of different performance levels. The present results confirm that the knee flexion before extension is a prerequisite for an efficient execution of the serve, whatever the performance level. However, several differences in performance parameters variables were identified between players of various performance levels. From the restricted to the normal serve condition, skilled players displayed larger increases in anteroposterior GRF and in ball impact locations than in other groups. Skilled players also performed faster serves than their less skilled counterparts, which are related to a forceful lower limb drive. Taken together, these results reinforce the role of lower extremities to produce an effective high-speed serve through possible mechanisms, including the use of coordinated movement and/or the use of elastic energy and muscle preload. However, further investigation is needed to better understand the relationships between lower extremity function and racquet kinematics among different players.

PRACTICAL APPLICATIONS

The daily and experienced observations of player movements by the coaches can be completed by numerical information to establish the optimal range of flexion extension in lower extremities for generating high-speed serves. The large involvement of the lower extremities in the tennis serve reinforces the importance of their strength and flexibility training to improve explosive power, speed, and endurance (33). Explosive strength or plyometric training is known to be useful for improving lower body strength. Plyometric training, such as bounding, jumping, and hopping, enhances the muscle's ability to generate power by optimizing stretch-shortening cycle. Plyometric training in addition to flexibility, cardiorespiratory endurance, general strength, and muscular endurance was shown to be efficient for improving general fitness and preventing injuries (7). Appropriate leg exercises in tennis also include isokinetics, weight machines, and rubber tubing systems. Considering that improvement in speed can also be caused by a better reaction time, coaches should prescribe exercises that invoke specific patterns (direction, amplitude, speed) of neuromuscular recruitment and activation. Also, plyometric medicine ball throws that activate trunk and upper arm muscles are efficient.

REFERENCES

1. ANDERSON, M.B. Comparison of muscle patterning in the overarm throw and tennis serve. *Res. Q.* 50:541–553. 1979.
2. BAHAMONDE, R., AND D. KNUDSON. Ground reaction forces of two types of stances and tennis serves. *Med. Sci. Sports Exerc.* 33:S102, 2001.
3. BAHAMONDE, R.E. Changes in angular momentum during the tennis serve. *J. Sports Sci.* 18:579–592. 2000.
4. BAHAMONDE, R.E. Joint power production during flat and slice tennis serves. In: *15th International Symposium on Biomechanics in Sports.* Denton, TX, 1997. pp. 489–494.
5. BARTLETT, R., J. PILLER, AND S. MILLER. A three-dimensional analysis of the tennis serves of National (British) and county standard players. In: *Science and Racket Sports.* T. Reilly, M. Hughes, and A. Lees, eds. London: E & FN Spon, 1995. pp. 98–102.
6. BRODY, H. *Tennis Science for Tennis Players.* Philadelphia: University of Pennsylvania Press, 1987.
7. CHANDLER, T.J. Exercise training for tennis. *Clin. Sports Med.* 14:33–46. 1995.
8. COHEN, D.B., M.A. MONT, K.R. CAMPBELL, B.N. VOGELSTEIN, AND J.W. LOEWY. Upper extremity physical factors affecting tennis serve velocity. *Am. J. Sports Med.* 22:746–750. 1994.
9. DRISS, T., H. VANDEWALLE, J. QUIEVRE, C. MILLER, AND H. MONOD. Effects of external loading on power output in a squat jump on a force platform: A comparison between strength and power athletes and sedentary individuals. *J. Sports Sci.* 19:99–105. 2001.
10. ELLIOTT, B., G. FLEISIG, R. NICHOLLS, AND R. ESCAMILIA. Technique effects on upper limb loading in the tennis serve. *J. Sci. Med. Sport.* 6:76–87. 2003.
11. ELLIOTT, B.C. Biomechanics of tennis. In: *Tennis*. A. Renström, ed. Oxford: Blackwell, 2002. pp. 1–28.
12. ELLIOTT, B.C. Biomechanics of the serve in tennis: A biomedical perspective. *Sports Med.* 6:285–294. 1988.
13. ELLIOTT, B.C. The development of racquet speed. In: *Biomechanics of Advanced Tennis.* B.C. Elliott, M. Reid, and M. Crespo, eds. London: ITF Ltd, 2003. pp. 33–47.
14. ELLIOTT, B.C., AND J. ALDERSON. Biomechanical performance models: The basis for stroke analysis. In: *Biomechanics of Advanced Tennis.* M. Crespo, ed. London: ITF Ltd, 2004. pp. 157–175.
15. ELLIOTT, B.C., K.G. BAXTER, AND T.F. BESIER. Internal rotation of the upper-arm segment during a stretch-shorten cycle movement. *J. Appl. Biomech.* 15:381–395. 1999.
16. ELLIOTT, B.C., AND R. KILDERRY. *The Art and Science of Tennis.* Philadelphia: Saunders College Publishing, 1983. p. 41.
17. ELLIOTT, B.C., T. MARSH, AND B. BLANKSBY. A three-dimensional cinematographic analysis of the tennis serve. *Int. J. Sports Biomech.* 2:260–271. 1986.
18. ELLIOTT, B.C., R.N. MARSHALL, AND G. NOFFAL. Contributions of upper limb segment rotations during the power serve in tennis. *J. Appl. Biomech.* 11:433–442. 1995.
19. ELLIOTT, B.C., AND G.A. WOOD. The biomechanics of the foot-up and foot-back tennis service techniques. *Aust. J. Sport Sci.* 3:3–6. 1983.
20. GIRARD, O., J.P. MICALLEF, AND G.P. MILLET. Lower-limb activity during the power serve in tennis: Effects of performance level. *Med. Sci. Sports Exerc.* 37:1021–1029. 2005.
21. GORDON, B.J., AND J. DAPENA. Contributions of joint rotations to racquet speed in the tennis serve. *J. Sports Sci.* 24:31–49. 2006.
22. KIBLER, W.B. Biomechanical analysis of the shoulder during tennis activities. *Clin. Sports Med.* 14:79–85. 1995.
23. KIBLER, W.B., AND D. VAN DER MEER. Mastering the kinetic chain. In: *World-Class Tennis Technique.* P. Roetert and J. Groppel, eds. Champaign, IL: Human Kinetics, 2001. pp. 99–113.
24. KRAEMER, W.J., K. HAKKINEN, N.T. TRIPLETT-MCBRIDE, A.C. FRY, L.P. KOZIRIS, N.A. RATAMESS, J.E. BAUER, J.S. VOLEK, T. MCCONNELL, R.U. NEWTON, S.E. GORDON, D. CUMMINGS, J. HAUTH, F. PULLO, J.M. LYNCH, S.J. FLECK, S.A. MAZZETTI, AND H.G. KNUTTGEN. Physiological changes with periodized resistance training in women tennis players. *Med. Sci. Sports Exerc.* 35:157–168, 2003.
25. LEES, A. Science and the major racket sports: A review. *J. Sports Sci.* 21:707–732. 2003.
26. LEES, A., J. VANRENTERGHEM, AND D. DE CLERCQ. Understanding how an arm swing enhances performance in the vertical jump. *J. Biomech.* 37:1929–1940. 2004.
27. LO, K.C., L.H. WANG, C.C. WU, AND F.C. SU. Kinematics of lower extremity in tennis flat and spine serve. *J. Med. Biol. Eng.* 24:209–212. 2004.
28. MILLER, D.I. Body segment contributions to sport skill performance: Two contrasting approaches. *Res. Q. Exerc. Sport.* 51:219–233. 1980.
29. MIYASHITA, M., T. TSUNODA, S. SAKURAI, H. NISHIZONA, AND T. MIZUNO. Muscular activities in the tennis serve and overhand throwing. *Scand. J. Sports Sci.* 2:52–58. 1980.
30. PAYNE, A.H. Comparison of the ground reaction forces in golf drive and tennis service. *Aggressologie* 19:53–54. 1978.
31. PETERSON, M.W. The segmental components in skilled baseball throwing. Master's thesis, University of Illinois, Urbana-Champaign, 1973.
32. PUGH, S.F., J.E. KOVALESKI, R.J. HEITMAN, AND W.F. GILLEY. Upper and lower body strength in relation to ball speed during a serve by male collegiate tennis players. *Percept. Mot. Skills* 3:867–872. 2003.
33. REID, M., A. QUINN, AND M. CRESPO. *Strength and Conditioning for Tennis.* London: ITF Ltd, 2003.
34. SCHONBORN, R. *Advanced Techniques for Competitive Tennis.* Aachen, Germany: Meyer and Meyer, 1999. pp. 1–280.
35. SIGNORILE, J.F., D.J. SANDLER, W.N. SMITH, M. STOUTENBERG, AND A.C. PERRY. Correlation analyses and regression modeling between isokinetic testing and on-court performance in competitive adolescent tennis players. *J. Strength Cond. Res.* 19:519–526. 2005.
36. SMITH, S.L. Comparison of selected kinematic and kinetic parameters associated with the flat and slice serves of male intercollegiate tennis players. Doctoral dissertation, Indiana University, 1979.
37. SPRIGINGS, E., R. MARSHALL, B. ELLIOTT, AND L. JENNINGS. A three-dimensional kinematic method for determining the effectiveness of arm segment rotations in producing racquet-head speed. *J. Biomech.* 27:245–254. 1994.
38. TOYOSHIMA, S., T. HOSHIKAWA, M. MIYASHITA, AND T. OGURI. Contribution of the body parts to throwing performance. In: *Biomechanics IV.* R.C. Nelson and C.A. Morehouse, eds. Baltimore: University Park Press, 1974.

39. VAN GHELUWE, B., I. DE RUYSSCHER, AND J. CRAENHALS. Pronation and endorotation of the racket arm in a tennis serve. In: *Biomechanics X-B.* B. Jonsson, ed. Champaign, IL: Human Kinetics, 1987. pp. 667–672.
40. VAN GHELUWE, B., AND M. HEBBELINCK. The kinematics of the service movement in tennis: A three dimensional cinematographical approach. In: *Biomechanics IX-B.* D.A. Winter, R.W. Norman, R.P. Wells, and A.E. Patla, eds. Champaign, IL: Human Kinetics, 1985. pp. 521–526.
41. VAN GHELUWE, B., AND M. HEBBELINCK. Muscle action and ground reaction forces in tennis. *Int. J. Sport Biomech.* 2:88–99. 1986.
42. WILSON, G.J., B.C. ELLIOTT, AND G.A. WOOD. The effect on performance of imposing a delay during a stretch-shorten cycle movement. *Med. Sci. Sports Exerc.* 23:364–370. 1991.

Acknowledgments

Thanks to Sebastien Racinais for help in statistical analysis.

Address correspondence to Olivier Girard, oliv.girard@gmail.com.