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Research article

The role of knee positioning and range-of-motion on the closed-stance forehand tennis swing

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Abstract

This paper discusses the role of knee positioning and range-of-motion on the closed-stance forehand tennis swing. The analyses of tennis swing mechanics were performed using a computer model comprised of a full-body model of a human and an inertial model of a racket. The model was driven by subject forehand swings (16 female college-level subjects) recorded with a high-speed digital motion analysis system. The study discovered that both initial knee positioning and range-of-motion were positively related to racket velocity and characteristic of more skilled players. The direct effects of knee positioning and range-of-motion on racket movement are minimal, however there are several indirect biomechanical effects on the forehand motion such as movement of the body mass center, work of the knee, hip and back joints, and the angular range-of-motion of the hips and torso. Some of these indirect effects were related to racket velocity and characteristic of more skilled players. Factors that influenced knee positioning and range-of-motion include years of playing, amount of coaching, and body style. Efforts to both increase and restrict the knee movements of the subjects resulted in substantially lower racket velocities (and other detrimental biomechanical effects) implying that there may be optimal knee positions and range-of-motion for a given subject. The most skilled subject exhibited a high degree of consistency of knee positioning and range-of-motion. This subject adjusted for varying ball height through modified initial knee positioning while maintaining fairly constant ranges-of-motion.

Key words: Biomechanical models, tennis swing, forehand, knee joint.

Introduction

Tennis is one of the most widespread and popular recreational sports that is popular all over the world (Kraemer et al, 1995). Biomechanical interest in the sport goes back as much as 55 years (Van Gheluwe and Hebbelinck, 1986). Since that time, investigators have examined many aspects of the forehand tennis swing such as shot accuracy, coordination, consistency, spin production, and biomechanical contributions to racket velocity (Bahamonde and Knudsen, 2003). Recently, much effort has been focused on the biomechanical analyses of the trunk and upper extremities during the forehand tennis swing especially by Bahamonde and Knudsen (1998a; 1998b; 1999; 2003), particularly comparing the open and closed stance styles. In addition, several researchers and teachers have identified lower extremity motion including the knees, as an important component of the closed stance forehand swing (Groppel, 1984; Bollettieri, 1984). Unfortunately, formal investigations on the role of the knees in the overall biomechanics of the forehand swing have been limited. Elliot (1980) provides a description of the proper closed stance forehand technique using a sequence of photographs which show that knee positioning and range-of-motion are important components the swing. The photographs also demonstrate the influence of knee positioning and range-of-motion on weight shifts, body CG movement, and hip and trunk rotations. Kraemer et al (1995) and Groppel (1994) noted that closed stance forehand swings are initiated in the knee-to-hip region of the body, and gradually build velocity up the whole kinematic chain. The generation of force production in tennis begins at the knee and is translated upward (Perry et al, 2004). Kraemer et al (1995) found high correlations between the strength measures of knee extension and flexion (both isometric and isokinetic) and ball velocities for female college players hitting a forehand shot. Response and movement times for tennis and tennis like movements were enhanced by the proper choice of knee angle during the preparatory stance phase (Cotton and Denning, 1970; Yamamoto, 1996). Iino and Kojima (2001) analyzed the kinetics of the lower extremities of collegiate level tennis players executing a closed stance forehand (with stationary feet) in an effort to determine the sources of pelvis superior-inferior torque. An outcome of this work was a general description of knee movements and graphical knee torque profiles during the swing. No relationships between knee movements/torques and racket velocity, skill level, or other body movements were described however. Van Gheluwe and Hebbelinck (1986) used force plate data to identify the forward motion of the body generated by knee movement in accelerating the body during the forward motion, then decelerating it just prior to impact.

Since the important role of the knees during a forehand swing is apparent yet formally unstudied, an in-depth biomechanical investigation of knee movements and related biomechanical effects would add to our understanding of the forehand tennis swing, and provide valuable information for coaches, sport scientists, and players regarding performance and tennis-specific training programs. This study focuses exclusively on the closed stance forehand. Typically, this style of forehand swing experiences more lower extremity motion than the open stance forehand. In addition, lower extremity motion is more important for generating power for the closed stance forehand for the open stance forehand (Groppel, 1984; Bahamonde and Knudson, 1998b; Bahamonde, 1999). Thus it is believed that knee movement has a more

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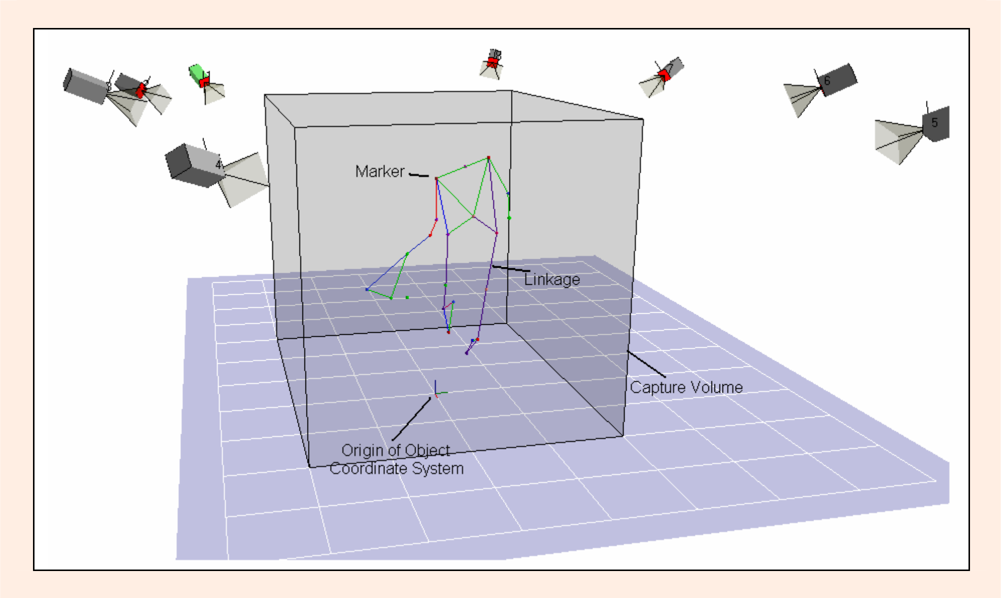

Figure 1. **Working volume and stick figure model of recorded tennis swing.**

fundamental role in this style of forehand swing motion than for an open stance forehand.

The direct effects of knee positioning and range-of-motion upon racket velocity during the closed stance forehand may be minimal since little racket movement occurs from knee movements alone. However, their appears to be several related biomechanical effects which may be indirectly related to racket velocity and characteristic of player skill level such as the movements of adjacent body segments, the overall body mass center, and the work done by various joints. The purposes of this study were to describe the initial positioning and range-of-motion of the knee joints during a closed stance forehand tennis swing, determine their direct and indirect biomechanical effects on the forehand motion, the relationships of these effects upon the racket impact velocities and player skill level, and the factors that effect knee positioning and range-of-motion.

Methods

Experimental procedures

Sixteen right-handed female advanced tennis players who were members of the Lafayette College tennis team (mean ± standard deviation: age, 20 ± 1.4 years; weight, 54.0 ± 5.7 kg; height, 1.61 ± 0.08 m) served as subjects. The relative skill level of the players was subjectively designated by their coach via an integer-based numerical ranking scheme. The players provided additional data regarding playing experience (11.2 ± 4.0 years) and amount of formal coaching/instruction (7.8 ± 2.4 years).

Informed consent for the following procedure was obtained from all subjects. Each subject had reflective markers placed upon her body and the racket as described below. All subjects used the same midsize medium string racket for consistency of racket inertia properties and mechanical response (Bahamonde and Knudson, 2003). After practicing for several minutes to acclimate to the markers, racket, and testing environment, the subjects were asked to execute a series of normal mid-level flat forehand shots using a closed stance. The closed stance is defined by Bahamonde and Knudson (2003) as “the body turned sideways to the net (hip perpendicular to the baseline) and, as the ball approached, the player takes a step forward toward the ball rotating the hips and trunk.” All trials were performed indoors with a ball machine projecting the ball at a waist-high level (adjusted for each subject) at approximately 15 m/sec. Six trials were recorded for each subject. The trial with the maximum ball velocity was selected (Knudson and Bahamonde, 1999). The subjects were not instructed that their knee positions and movements were being investigated.

After these trials, each subject was instructed to repeat the closed stance forehand swing while increasing by approximately 33% the pre-bending and range-of-motion of the knees. In addition, each subject was instructed to repeat the closed stance forehand swing while decreasing by approximately 33% the pre-bending and range-of-motion of the knees. Several practice trials were run in an effort to have the subject become comfortable with the increased/decreased movement trials. Once a relative level of comfort was obtained, the subject swings were again recorded and selected in the same manner as described above.

Extra trials were run with the most skilled player to investigate the consistency of knee positions and range-of-motion for a given ball height (20 trials), and to determine the effects of ball height on knee positions and range-of-motion (10 trials at mid-thigh level and 10 trials at mid-torso level). These trials, while outside the scope of the wider study, were intended to provide context for the results obtained from the subject group, and to suggest possible areas of further study.

An eight camera Motion Analysis Corporation system was used to track passive-reflective markers that were placed upon the player and the racket. The system utilized Eagle digital cameras (1280 x 1024 resolution) and operated at 200 frames per second. There were 23 markers (13 and 19 mm in diameter) placed on the player, and three on the racket. On the player the markers were located at the wrists, forearms, elbows, shoulders, cervical and lumbar vertebra, head, hips, knees, mid lower leg, ankles, and feet. All markers were located relative to bony landmarks for consistency, and securely attached with two-sided tape (skin) or Velcro (clothing). Markers were attached directly to the skin wherever possible. Subjects wore snug-fitting clothing (tank-top and bicycle-style shorts), a baseball hat (head marker), and shoes of their choice. Marker/joint offsets were measured, and virtual joint-center markers were located from these data using features provided by the data collection software. Reflective tape was attached to the tennis ball to determine the precise time of impact.

The three-dimensional marker paths were recorded at 200Hz then smoothed with a Butterworth Filter Algorithm (Motion Analysis, 2004) then processed to yield global body *1-2-3* angular motions of each body segment and the racket. The global angular motions were transformed into local relative joint position angles by comparing the orientations of adjacent body segments using processes described in Craig (1986). These relative joint angles were used to kinematically drive the joints of the computer model. Figure 1 shows the camera locations, the working volume, global origin, and a stick figure representation of a subject during forehand swing.

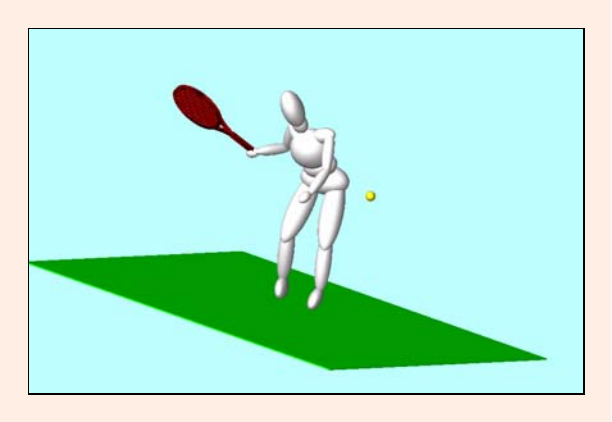

Figure 1. Working volume and stick figure model of recorded tennis swing.

Computer mdel

A full-body model of a human coupled to a parametric model of a tennis racket was developed to determine the kinematic and kinetic quantities necessary for this study (see Figure 2). The computer model was built, analyzed, and post-processed with the aid of the commercial software packages ADAMS (Mechanical Dynamics, Inc.) and LifeMod humanoid pre-processor (Biomechanics Research Group, Inc.). ADAMS is a multi-body dynamic analysis program where models are built from rigid segments connected with flexible elements and/or a variety of joints. Forces and motions can be superimposed on the model. ADAMS derives the differential equations of motion for the model employing methods of Lagrangian dynamics. The equations of motion are solved using one of several backward differentiation formula (BDF) integrators. The results are output and the model is simulated using the ADAMS postprocessor. This modeling approach has been used to analyze the tennis swing and racket behavior (Nesbit et al, 2006), as well as other sports motions and equipment behavior (Nesbit, 2007).

The player was modeled as a variable full-body, multi-link, three-dimensional humanoid mechanism made up of seventeen rigid segments interconnected with joints. The model was configured with the following fifteen body segments; head, neck, thorax, lumbar, pelvic, upper arm (2), forearm (2), thigh (2), lower leg (2), hand (2), and foot (2). All segments were defined by their adjacent joints with exceptions of the neck (C1-C8), thorax (T1-T12), and lumbar (L1-L5 and S1-S5) which were defined by the associated vertebrae. The segment size, mass and inertia properties were determined from gender, age, and overall body height and weight using the GeBod data base accessible through the ADAMS software. The model consisted of the following sixteen joints; ankles (2), knees (2), hips (2), lumbar, thoracic, neck, shoulders (2), elbows (2), and wrists (2). All joints were spherical yielding a maximum of three relative angular degrees-of-freedom with the exceptions of the knees and elbows which were modeled as single degree-of-freedom revolute joints. The motions superimposed upon the joints were specified in terms of Bryant angles (see below) and their time dependent derivatives.

The body segment reference coordinate systems, established when the model is posed in the standard anatomical position, places the Z-axis pointing downward with the exception of the feet which point forward parallel to the long axis of the foot segment. The X-axis points outward from the body, and the Y-axis completes a right-handed coordinate system. Joint motions, forces, and torques are of the distal body segment coordinate system relative to the proximal body segment coordinate system. The angular quantities are specified according to the relative body (Euler angle) 1-2-3 Bryant angle convention where alpha motion (α) is about the X-axis, beta motion (β) is about the Y'-axis, and gamma motion (γ) is about the Z''-axis (Kane et al., 1983).

The racket was modeled as a rigid structure with representative mass and inertia properties (see Figure 3) using the methods described in Nesbit (2006). The mass (0.324 kg), mass center location (314.6 mm from end of handle), and three principal inertia values (I_{GX} = 14,613 kg-mm-s^{-2}; I_{GY} = 13,394 kg-mm-s^{-2}; I_{GZ} = 1007.3 kg-mm-s^{-2}) were determined using an inertia pendulum (Brody, 1985). The connection between the racket and the hand was modeled as perfectly rigid with no damping. This rigid body approach to the modeling of the human/racket connection was similar to the methods of Bahamonde and Knudson (2003) and Elliot et al. (2003) in studying swing mechanics.

A ground surface model was added to support the humanoid model using methods described in Nesbit et al. (1994). A standard linear spring-damper system was used to represent the contact between the feet and the ground, and frictional forces provided traction. The initial contact parameters were obtained from Scott et al. (1993) and were adjusted at solution time to prevent over-stiffening the model. The humanoid model was balanced by kinematically driving the angular DOF's of the lower torso segment (hips) relative to the global coordinate system. To avoid over-constraining the model, the linear DOF's were set free. The ground reaction forces determined by this modeling approach yield reasonable results compared to force plate data when used to study golf swing mechanics (Nesbit, 2007). For this study, the mean peak total vertical ground reaction forces as determined by the model were 127 ± 3% of the subject's body weight which agrees well with the force plate data of Iino and Kojima (2001) and Van Gheluwe and Hebbelinck (1986) who each report total ground reaction forces for one representative subject.

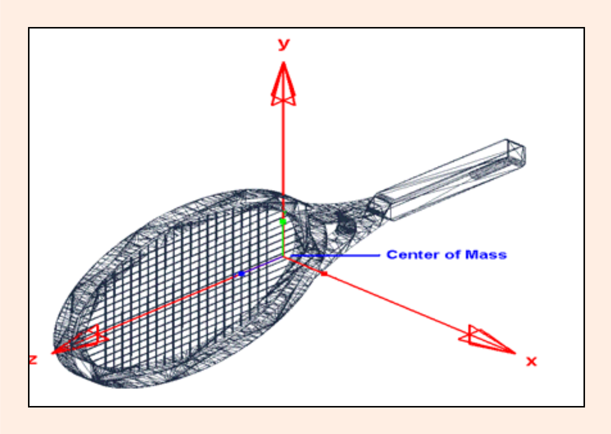

Figure 3. Racket model indicating mass center and principal coordinate system.

Force plate data were not obtained for this study since is was not possible to consistently predict the subjects' foot placements for the forehand shot. Other studies of the closed forehand did use force plates (Iino and Kojima, 2001; Van Gheluwe and Hebbelinck, 1986), however the subjects in these studies were instructed not to move their feet while swinging the racket. Either forcing the subjects to keep both feet in a stationary position, or requiring them to step in a predefined manner in order to ensure consistent contact with force plates was thought to be detrimental to the goals of the study. Allowing the subjects to freely move their feet without being conscious of their placement was believed to result in more representative knee movements. However the consequence of determining joint moments via inverse dynamics without force plate data are possible large errors in the kinetic results predicted by the model. Thus the reader must consider the kinetic results predicted by the model within this possibility.

Solution, output, and verification of model

The humanoid and racket components of the model are rigid and kinematically driven yielding simultaneous linear equations. However the ground-surface model introduced non-linearities and time-dependent dynamic responses into the system. Thus, the entirety of the model represents a forward dynamics problem requiring numerical integration to solve. The resulting dynamic equations of motion were solved using a Wielenga Stiff Integrator (Mechanical Dynamics Inc.). Solution of the model yielded the kinematic and kinetic quantities of the body joints, the macro body mass center (CG) trajectories, racket kinematics, racket/hand interaction forces and torques, and ground reaction forces. The work of the body joints were determined from the joint kinematic and kinetic data using methods described in Nesbit and Serrano (2005) which are summarized in Appendix. General verification of this modeling approach and model output was done with force plate data, static anatomical posturing, and simple harmonic joint motions (Nesbit et al., 1994 and Nesbit, 2007). Where available, data from this study are compared to previously published data to support the modeling approach (see above for ground reaction forces). However the amount of kinematic and kinetic data reported in the literature for the lower extremities for a closed-stance forehand swing are limited and is provided mainly by Iino and Kojima (2001) and Van Gheluwe and Hebbelinck (1986).

Modeling sensitivity analysis

A sensitivity analysis was performed to determine the effects of small changes/errors to modeling parameters on the kinematic and kinetic results predicted by the model. The number of parameters involved in this model is considerable. Each body segment has associated length, mass, mass center (CG) location, and inertial properties. The racket model adds its own mass, CG location, and inertial properties to the overall model. The body segment modeling parameters of length, mass, CG location, and inertial properties were determined from population parameters (gender, age, height, and weight), thus represent average values. As such the segment modeling

Table 1. Knee positions and ROM and Correlations to Subject data.

Independent Variable	Mean (deg)	SD (±) (deg)	Racket Vel (R^2)	Skill Level (R^2)	Height (R^2)	Wght (R^2)	Coach (R^2)	Years Played (R^2)
Rear Knee Initial Pos: Setting Phase	27.4	5.7	.187	.212	.230	----	----	.190*
Rear Knee ROM: Setting Phase	8.1 (flex)	3.8	.304	.316	----	---	---	.220
Front Knee Initial Pos: Swing Phase	55.5	11.3	.595	.470	.214*	----	.230	.121*
Rear Knee Initial Pos: Swing Phase	36.5	6.3	.305	.422	.244	---	.268	.189
Front Knee ROM: Swing Phase	24.7# (exten)	15.2	.325	.311*	----	----	.241*	.140*
Rear Knee ROM: Swing Phase	25.8 (flex)	7.4	.489	.372	----	----	.293	.177

All variables are significant at $p<0.05$ unless indicated by *. # A minority of subjects exhibited further flexion of the front knee during the swing phase

Table 2. Body CG displacements and correlations with knee positions and ROM.

Body CG Displ Comp	Mean (cm)	SD (±) (cm)	Rear Knee IP: Setting (R^2)	Rear Knee ROM: Setting (R^2)	Front Knee IP: Swing (R^2)	Rear Knee IP: Swing (R^2)	Front Knee ROM: Swing (R^2)	Rear Knee ROM: Swing (R^2)
Vert Displ: Setting	-9.4	3.5	----	.309	.388	----	----	----
Horiz Displ: Setting	14.5	4.9	----	----	.394	----	----	----
Vert Displ: Swing	14.3	5.2	----	----	.524	----	.619	----
Horiz Displ: Swing	4.1	2.1	----	----	----	----	----	.246*

Note: All variables are significant at p<0.05 unless indicated by *

parameters may be slightly different from the actual subject values. A sensitivity analysis was performed using variations of ± 30mm on segment length and mass center location, and ± 10% on inertial properties as suggested by the literature references of Reinbolt et al (2007). These variations were applied to the left (front) lower leg segment, and the effects upon the kinematic and kinetic quantities of the adjacent ankle and knee joints were determined. The joint kinematic quantities were not affected by changes in the inertial properties or location of the mass center. These results were expected for kinematically driven joints. The effects of small changes in segment mass, CG location, and inertial properties when done individually had relatively linear effects on the adjacent joint toques. The change in joint torque in every case was either near or below the percentage change to the mass, CG location, or inertia value. Changes in link lengths had the largest overall effect on the joint kinematic and kinetic quantities. The joint angles for the adjacent joints were affected to a small degree. This effect was magnified slightly for the joints velocities and accelerations. Joint torque values changed by as much as the square of the change in segment length. It appears that the model is kinematically robust for small changes in all segment modeling parameters. However, small changes in segment lengths had moderate effects upon joint torque values. Thus the joint kinetic quantities predicted by the model should be viewed within this context.

Results

For the purposes of describing the knee movements for a closed-stance forehand swing during the forward movements of the swing, the swing is divided into two distinct phases. The first phase, referred to herein as the setting phase, is the portion of the swing that occurs from the initiating of the forward stepping motion of the front foot until the heel of the front makes contact with the ground. The second phase, referred to herein as the swing phase, is the portion immediately after the heel of the front foot makes contact with the ground until impact. This division of the forward portion of the closed-stance forehand swing is similar to that described by Iino and Kojima (2001).

The independent quantities of interest for this study were forward and rear knee initial flexed positions, and forward and rear knee ranges-of-motion. A fully extended knee was designated as zero degrees. Knee range-of-motion was determined from the difference in knee angular position from the beginning to end of a particular phase. Results are presented as mean ± standard deviation and correlations will be presented as coefficient of determination values (R^2). The statistical significance level was set at $p < 0.05$.

Racket velocity and skill level

The mean resultant racket velocity at impact was 12.91 ± 2.4 m/sec which is less than reported by Knudson and Bahamonde (1999) for intermediate players (16.1 ± 2.5 m/sec), however their group included male players. It is well below the 28.2 ± 3.3 m/sec reported by Iino and Kojima (2001) for a group of all male subjects. A strong relationship ($R^2 = 0.540$, $p < 0.05$) was observed between skill level and racket velocity within the group which is consistent with the findings of Knudson and Bahamonde (1999). This finding between skill level and racket velocity is based upon an integer ranking scheme that was subjectively applied by the subjects' coach. While this ranking system appears to be sound, this qualification on relationships with skill level applies throughout this paper.

Initial positions and range-of-motion

The mean and standard deviations of the initial position and range-of-motion (ROM) of the rear knee during the setting phase, and the initial positions and ROM of both knees during the swing phase are presented in Table 1. In addition, the correlations of these variables with subject data are also presented. The data from Table 1 indicates that knee positioning and range-of-motion are related to

Table 3. Work of knee joints and correlations with knee positions and ROM.

Knee Joint Work	Mean (Nm)	SD (±) (Nm)	Rear Knee IP: Setting (R^2)	Rear Knee ROM: Setting (R^2)	Front Knee IP: Swing (R^2)	Rear Knee IP: Swing (R^2)	Front Knee ROM: Swing (R^2)	Rear Knee ROM: Swing (R^2)
Rear:Setting	-32.1	13.9	.327	.581	N/A	N/A	N/A	N/A
Front:Setting	0	0	N/A	N/A	N/A	N/A	N/A	N/A
Rear:Swing	10.0	5.6	N/A	N/A	---	.217*	---	.411
Front:Swing	36.4	10.9	N/A	N/A	.240	---	.623	---

Note: All variables are significant at p<0.05 unless indicated by *

Table 4. **Hip and trunk rotations and correlations with knee positions and ROM.**

Hip Trunk Rotat	Mean (Nm)	SD (±) (Nm)	Rear Knee IP: Setting (R^2)	Rear Knee ROM: Setting (R^2)	Front Knee IP: Swing (R^2)	Rear Knee IP: Swing (R^2)	Front Knee ROM: Swing (R^2)	Rear Knee ROM: Swing (R^2)
Hip: Setting	-7.8	2.8	----	.338	----	----	----	----
Trunk:Setting	-17.4	4.6	----	.244	----	----	----	----
Hip: Swing	72.4	9.4	----	----	.132*	.179*	----	.652
Trunk:Swing	97.8	12.7	----	----	----	----	.374#	.414

All variables are significant at $p<0.05$ unless indicated by *. # This correlation is only for subjects that extended their front knee during the swing phase. There was no correlation found for those subjects that flexed their front knee during the swing phase.

racket velocity and characteristic of skilled players. However since knee positioning and range-of-motion have little direct effect on the motion of the racket, their role in the closed-stance forehand swing is secondary in facilitating and supporting other important biomechanical movements of the swing. To identify the most important of these secondary effects, the independent knee position and range-of-motion quantities during both phases of the swing were related to various biomechanical movements and kinetic quantities available from the computer analyses. The most significant of these secondary effects were found to be body CG displacements, work of the knee joints, hip/trunk rotations, and core body work.

Secondary biomechanical effects

Tables 2 through 5 respectively present the body CG displacements, work of the knee joints, hip/trunk rotations, and core body work, and their correlations to knee positions and range-of-motion during both phases of the swing. The body CG displacements of Table 2 include the minor contribution from the movement of the mass of the racket. The work of the knee joints and the correlations to knee positions and range-of-motion during both phases are presented in Table 3. The rotations of the hips and trunk presented in Table 4 were determined as projections of the lines connecting the hip joint centers and shoulder joint centers upon the horizontal plane. This convention was established by Iino and Kojima (2001) thus it is used here to facilitate comparisons of results. Relative rotations are reported since the consistent establishment of an global angular origin was found to be difficult. Relative rotations in the direction of the forward movement of the racket are forward or positive. The core body work presented in Table 5 is the defined as the sum of the work produced by the hips and back joints (lumbar and thoracic).

Secondary biomechanical effects related to racket velocity and skill level

Knee positioning and range-of-motion have significant effects on body CG displacement, knee work, core body work, and hip and trunk rotations. These knee affected biomechanical quantities were correlated to racket velocity and subject skill level with the results given in Table 6. Single value representations of the these quantities were found to better characterize their contribution to the forehand motion. The overall displacement of the body CG represents the vector sum of the displacements of the two phases. The total knee work is the net total of the work of both knees during the setting and swing phases. The total body core work is the net total of the core body work during the setting and swing phases. The total hip/trunk rotation is the sum of the range-of-motions of the hip and trunk during both phases of the swing.

Table 6. **Knee affected biomechanical quantities and subject data.**

Knee Affected Quantities	Racket Vel (R^2)	Skill Level (R^2)
Overall Body CG Displacement	.436	.611
Total Knee Work	----	.210*
Total Hip/Trunk ROM	.564	.498
Total Core Body Work	.679	.655

All variables are significant at $p<0.05$ unless indicated by *

Discussion

Knee positioning and range-of-motion

The data and correlations presented in Table 1 data tend to support the important role of the knees in prepositioning and executing a closed-stance forehand swing. For the setting phase of the swing, the range-of-motion of the rear knee was more important for generating racket velocity than the initial positioning of the rear knee angle.

In addition, the range-of-motion of the rear knee appears to be a characteristic of a more experienced and skilled player. Both rear knee positioning and range-of-motion appear to be independent of coaching, and (mostly) body type. For the swing phase of the motion, the initial positioning of the front knee was more important than the initial positioning of the rear knee in generating racket velocity. The correlation of the initial positioning of the front knee with racket velocity proved to be the strongest overall, and may be an indication of an aggressive forward step in moving toward the ball during the setting phase. Both initial knee positions appear to be characteristics of more skilled players. In addition, it appears that coaching may affect these quantities somewhat, and that body type may have an influence. The

Table 5. **Core body work and correlations with knee positions and ROM.**

Hip Trunk Rotat	Mean (Nm)	SD (±) (Nm)	Rear Knee IP: Setting (R^2)	Rear Knee ROM: Setting (R^2)	Front Knee IP: Swing (R^2)	Rear Knee IP: Swing (R^2)	Front Knee ROM: Swing (R^2)	Rear Knee ROM: Swing (R^2)
Setting phase	117	39.6	----	.354	----	----	----	----
Swing phase	268	67.3	----	----	.312	----	.442	.341

All variables are significant at $p<0.05$ unless indicated by * range-of-motion of both knees during the swing phase was important for generating racket velocity, with the rear knee being slightly more important. The knees move in opposite directions during this phase of the swing for most subjects with the front knee extending and the rear knee flexing. The range-of-motion of both knees was a characteristic of more skilled players. Coaching and experience had the highest degree of influence on knee range-of-motion during this phase of the swing. Range-of-motion was independent of body type characteristics. Note that some of the above correlations to player experience, coaching, and body type were found to be non-significant ($p > 0.05$).

None of the data in Table 1 have been previously reported with the exception of rear knee range-of-motion during the setting phase. The result presented here does not agree with Iino and Kojima (2001) who reported rear knee extension movement during this phase, however their subjects were instructed to keep both feet in contract with the ground during the entire swing.

Body CG displacement

The data and correlations presented in Tables 2 and 6 show that body CG displacements are affected by knee positioning and range-of-motion, and that overall body CG displacement was a characteristic of player skill and an indicator of racket velocity. During the setting phase of the swing the body CG dropped and moved forward. The downward movement was somewhat related to the flexion range-of-motion of the back knee during this phase of the swing, and the initial position of the front knee at the beginning of the swing phase. The forward movement of the body CG during this phase was independent of the position and range-of-motion of the rear knee, however it to was related to the initial position of the front knee at the beginning of the swing phase. According to Iino and Kojima (2001) the primary action contributing to the forward movement of the body CG is the abduction movement of the rear hip joint.

During the swing phase the body CG rose and moved forward. The upward movement of the body CG was strongly related to the initial position of the front knee at the beginning of this phase, and the extension range-of-motion of the front knee. The small forward movement of the mass center during this phase was slightly (and non-significantly) related to the flexion range-of-motion of the rear knee which combined with the continued abduction movement of the rear hip joint, rotation of the hip and trunk, and the forward motion of the racket to move the body CG forward.

Tracking the position of the body CG revealed two distinct body movements during the forehand swing. During the setting phase the body CG moved linearly forward and downward under the action of both knees with front knee positioning being the most important factor. During the swing phase, the body CG primarily moved upward while the major rotations of the hips and trunk took place. The positioning and range-of-motion of the front knee were the most important factors during this phase. These two distinct body motions are used to generate momentum; linear momentum during the first part of the swing as the player steps forward toward the ball, and angular momentum from the rotation of the legs, hips, and trunk (Bahamonde, 1999).

Work of the knee joints

During the setting phase the rear knee did negative work in decelerating the body as the CG dropped and ultimately reached its lowest point during this phase. The front knee did no work until it made contact with the ground at the end of the setting phase. The rear knee initially did positive work at the beginning of the swing phase (15.0 N-m) in pushing off the ground while extending the knee slightly. The rear knee then did a small amount of negative work during the remainder of the swing phase (-5.0 N-m) as the knee changed function from doing work to mostly providing structural support. The negative work resulted from the extension “supporting” torques applied over slight flexion of the knee. Initially the front knee does negative work (-8.5 N-m) for a short period of time in stopping the downward motion of the body CG, and decelerating the forward motion of the body CG (Van Gheluwe and Hebbelinck, 1986). The front knee then transitioned to positive work throughout the remainder of the swing phase in raising the body CG (44.9 ± 12.9 N-m).

As expected, the work of each knee was strongly related to their respective range-of-motion and the magnitudes of the extension/flexion torque. This finding was not surprising noting that the definition of mechanical work of a body joint. The knee joints contributed a net mean total of 14.3 N-m of work during the setting and swing phases to the overall work of the body in swinging the racket. The mean overall body work done during the two phases was 568 ± 122 N-m, thus the knees contributed very little to the overall body work (2.5%). Total knee work was weakly (and non-significantly) related to skill level. There was no relationship between knee work and racket velocity.

These findings support the notion that the knees themselves have little direct effect on swinging the racket. Their role appears to be secondary in initiating the swing motion (Kraemer et al, 1995; Groppel, 1994) and force production (Perry et al, 2004), providing structural support while velocity is built-up the kinematic chain, and facilitating other biomechanical actions that do effect racket velocity.

Hip/trunk rotations

The data and correlations presented in Tables 4 and 6 show that hip and trunk rotations are affected by knee positioning and range-of-motion, and that total hip and trunk range-of-motion was a characteristic of player skill, and an indicator of racket velocity (Bahamonde and Knudson, 1998a). During the setting phase both the hips and the trunk rotated backwards. For all subjects, the backward rotations of the hips and trunk reached their extreme positions at the end of the setting phase. There were slight relationships between the range-of-motion of the rear knee during this phase and the amount of backwards hip and trunk rotations. Initial rear knee positioning did not affect these values.

During the swing phase both the hips and trunk exhibited considerable forward rotations. The values for the trunk rotations agree almost exactly with Iino and Kojima (2001), however the hip rotations are about 12 degrees greater than they reported. There was a strong relationship between the range-of-motion of the rear knee during this phase and the amount of forward hip rotation, and a moderate relationship between the range-of-motion of the rear knee and the amount of forward trunk rotation. The range-of-motion of the front knee during this phase and the amount of forward hip rotation were moderately related for the subjects that extended their front knee. There was no significant relationship between the range-of-motion of the front knee and the amount of forward hip rotation for the few subjects that flexed their front knee during the swing phase. The range-of-motion of the front knee was not related to trunk rotation. Initial knee positioning during the setting was weakly (and non-significantly) related to hip rotation, and was not related to trunk rotation.

Knee range-of-motion appears to be a contributing factor to the rotation of the hips and trunk for a closed-stance forehand swing which is important since trunk rotation is significantly correlated with racket velocity. This finding supports the notion that the traditional square-stance technique gradually builds velocity up the whole kinematic chain of the body Groppel (1994).

Core body work

The data and correlations presented in Table 5 show that the core body work is affected by knee positioning and range-of-motion. During the setting phase the majority of the core body work was produced by abduction action of the rear hip. This hip abduction movement coincided with flexion of the rear knee which resulted in the core body work being related to the range-of-motion of the rear knee. During the swing phase, the remainder of the core body work was produced primarily from high hip torques and moderate lumbar and thoracic joint torques applied over their respective ranges-of-motion. This portion of the core body work was related to the range-of-motion of the front knee, the range-of-motion of the back knee, and the initial position of the front knee. It appears that an important function of the knees is to facilitate the pre-twisting and range-of-motion of the hips and back in creating angular distances over which torques can be applied and thus useful core body work produced.

The total core body work, which represents a majority of the total body work (67.8%), was a characteristic of a skilled player and a strong indicator of racket velocity. This finding partially supports the conclusions offered by Iino and Kojima (2001) and Kraemer et al (1995) that hip and leg torques, which are contributing factors to core body work, are important for generating upper body rotation, high racket speed, and force transfer to the racket.

Increased/decreased knee movements

In addition to normal trials, each subject was instructed to repeat the closed-stance forehand swing while first increasing by approximately 33%, then decreasing by approximately 33% the initial knee positioning and range-of-motion. It was found that in both cases the subjects had some difficulty in hitting the ball consistently. In addition, the subjects did not modify their knee positions and movements consistently among each other. The results and discussions which follow should be tempered by these inconsistencies in the trials. For the case of increased knee positioning and range-of-motion, the subjects lost on average 17% of their racket velocity. Overall body CG displacement increased by 22% as did total knee work (27%). The forward rotations of the hips and trunk decreased (13% and 9% respectively) which resulted in a decrease in the core body work (15%). For the case of decreased knee positioning and range-of-motion, there was an average reduction of 29% of racket velocity. Overall body CG displacement decreased by 46%, total knee work decrease by 59%, forward rotations of the hips and trunk decreased by 23% and 15% respectively, and core body work decreased by 31%. While these extremes represent possible irregular tennis swings for the subjects, the results do provide some insight to the role of the knees and validation of the relationships described previously.

Initial knee positioning and range-of motion were shown to be positively related to racket velocity and characteristic of skilled players. However from these trials there was no evidence that artificially increasing their values had any immediate beneficial effects on the racket velocity. It cannot be concluded however that this will always be the case since only a short period of time was given to adapt to these changes in swing mechanics. These results do suggest that there may be optimum values of initial knee positioning and range-of-motion for a given height of the tennis ball. How these optimum values are arrived at is not certain since the factors that influenced knee positioning and range-of-motion were weakly correlated at best. Yamamoto (1996) identified an optimum knee flexion angle (24.8 degrees for both knees) during the preparatory stance for the initiation of quick trunk rotation movements. While these movements were generic in nature, they were representative of sports movements such as the tennis swing. Interestingly, it was found that that optimum knee flexion angle during the preparatory phase was not necessarily the preferred angle of the subjects implying that there may be an opportunity to improve reaction times by the better choice of knee flexion angle.

Description of knee mechanics for most skilled subject

The knee positions and movements, and their related biomechanical effects identified above are described for the most skilled subject used in this study. This description is intended as a case study as opposed to an ideal example. In addition, this case study provides a context for describing and summarizing the overall knee movement mechanics and related biomechanical effects.

There appears to be two somewhat distinct phases to the forward portion of the closed-stance forehand swing regarding knee positioning and movement which coincide with other distinct actions of the body and racket. During the setting phase the rear knee positioning and range-of-motion function to lower and advance forward the body CG, counter-rotate the hip and back joints, and initiate the core body work to move the body CG forward. The rear knee does negative work to

Table 7. **Knee positions and Range-of-Motion (ROM) values for most skilled subject.**

Knee Quantity (degrees)	Average	Mean	SD	Range
Rear Knee Position Setting Phase	32	31	2.4	28-36
Rear Knee ROM Setting Phase	7 (flexion)	8	1.9	5-11
Rear Knee Position Swing Phase	39	37	2.6	34-42
Rear Knee ROM Swing Phase	29 (flexion)	30	3.9	25-37
Front Knee Position Swing Phase	58	58	2.7	54-63
Front Knee ROM Swing Phase	38 (extension)	36	4.8	30-44

decelerate the downward motion of the body CG. The end of the phase is marked by the coincident actions of achieving the lowest position of the body CG, the extreme rearward position of the racket, the extreme rearward rotated positions of the hips and back joints, and contact of the heel of the front foot with the ground. During the setting phase for the most skilled subject, her initial rear knee position was 32 degrees while the front foot was off the ground. She stepped forward approximately 28 cm while further flexing her rear knee 7 degrees. This combination of movements caused the body CG to lower 10.4 cm and move forward 12.9 cm. The rear knee did -36.0 N-m of work in decelerating the downward motion of the body CG. The core body work produced was 129 N-m which served to move the body CG forward. The hips rotated -10 degrees, and the torso rotated -23 degrees to achieve their extreme rearward rotated positions which coincided with the extreme rear position of the racket, and the heel of the front foot contacting the ground. At the end of the setting phase, the subject has achieved a favorable biomechanical configuration by creating a greater distance over which to apply the hip, back, and shoulder torques thus increasing the potential to do work to create racket velocity. With both feet on the ground the subject has the necessary traction forces to transition from the primarily linear motions of the setting phase to the major rotational motions of the swing phase.

During the swing phase the initial knee positioning and range-of-motion function together to mostly raise the body CG, initiate and support the forward rotation of the hip and back joints, and maximize the core body work. At the beginning of the swing phase the front knee does negative work which serves to decelerate the forward linear motion of the body CG. Simultaneously the rear knee does positive work in pushing off the ground while extending the knee slightly. This combined action serves to initiate and facilitate the rotation of the hips and trunk. The front knee then transitions to positive work to raise the body CG while the rear knee does little work as it mostly provides structural support for adjacent hip rotations. The end of this phase is marked by impact. During the swing phase for the most skilled subject, her initial front knee position was 58 degrees, and her initial rear knee position was 39 degrees. During this phase she extended her front knee 38 degrees and further flexed her rear knee 29 degrees. The combined action of these knee movements caused the body CG to raise 16.1 cm and move forward 3.9 cm. The hips rotated 76 degrees in the horizontal plane and the trunk rotated 105 degrees in the horizontal plane. During this phase, the front knee initially did -10.6 N-m of work in decelerating the forward linear motion of the body CG, then 50.9 N-m in raising the body CG. The rear knee initially did 17.2 N-m of work in pushing off the ground, then -6.1 N-m of work while mostly supporting the hips during their rotation. The total core work produced during the swing phase was 337 N-m. The resulting racket velocity at impact was 15.1 m/sec.

Twenty trials were run for the most skilled subject to determine the distribution of the independent knee quantities. Table 7 presents the average, mean, standard deviation, and range of the independent knee quantities for these trials. The most skilled subject exhibited a high degree of consistency in initial knee positioning and range-of-motion for both phases of the swing for a given ball height. While the data in Table 7 are informative and provide some context for the data from the subject group, it is not known whether these distributions of knee positions and range-of-motions are typical, or a characteristic of player skill. Further testing perhaps of the type presented by Knudson (1990) is necessary before any conclusions can be drawn.

Additional trials were run to determine the effects of ball height on knee positions and range-of-motion for the most skilled subject. Table 8 summarizes the independent knee quantities for the ten trials each above (mid-torso) and below (mid-thigh) the mid-waist ball position. While no definitive conclusions can be drawn from the this limited aspect of the investigation, it appears that adjustment to varying ball height is through changing initial positioning of the knees. It is possible that knee range-of-motion is nearly independent of the ball height and represents a nearly constant characteristic of the forehand swing itself. Again, further testing on a wider group is necessary before any conclusions can be drawn.

Table 8. **Knee positions and ROM values for variable ball height.**

Knee Quantity (degrees)	Mid-Thigh (degrees)	Mid-Waist (degrees)	Mid-Torso (degrees)
Rear Knee Position Setting Phase	48	32	26
Rear Knee ROM Setting Phase	5 (flexion)	7 (flexion)	7 (flexion)
Rear Knee Position Swing Phase	53	39	33
Rear Knee ROM Swing Phase	25 (flexion)	29 (flexion)	27 (flexion)
Front Knee Position Swing Phase	69	58	52
Front Knee ROM Swing Phase	34(extension)	38 (extension)	35 (extension)

Conclusion

Knee positioning and movement have long been advocated as important for the tennis closed-stance forehand swing. To scientifically investigate the role of knee positioning and movement for the closed-stance forehand swing, a full-body computer model of a human and an inertial model of a racket were combined and used to simulate and analyze the swing mechanics of sixteen female college-level subjects. The study verified that initial knee positioning and range-of-motion were positively related to racket velocity and characteristic of more skilled players. The effects of initial knee positioning and range-of-motion were directly related to the movement of the body mass center, work of the knee, hip and back joints, and the angular range-of-motion of the hips and torso. Some of these secondary effects were related to racket velocity and characteristic of more skilled players. There may be optimum values for initial knee positioning and range-of-motion since efforts to both increase and restrict the knee movements of the subjects resulted in substantially lower racket velocities as well as other detrimental biomechanical effects. If this is the case, how a player reaches these optimum values is not certain since the factors that influenced knee positioning and range-of-motion were weakly correlated at best. Further analyses of the most skilled subject revealed a high degree of consistency of knee positioning and range-of-motion for a given ball height. This subject adjusted for varying ball heights through modified initial knee positioning while maintaining fairly constant ranges-of-motion. These two findings warrant further investigations.

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Key points

- Initial knee positioning and range-of-motion were positively related to racket velocity and characteristic of more skilled players for the closed stance forehand motion.
- Knee positioning and range-of-motion had several indirect biomechanical effects on the forehand motion such as movement of the body mass center, work of the knee, hip and back joints, and the angular range-of-motion of the hips and torso.
- Efforts to both increase and restrict the knee movements resulted in substantially lower racket velocities implying that there may be optimal knee positions and range-of-motion for a given subject.
- The most skilled subject exhibited a high degree of consistency of knee positioning and range-of-motion. This subject adjusted for varying ball height through modified initial knee positioning while maintaining fairly constant ranges-of-motion.

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APPENDIX
(Work of the Body Joints)

The mechanical work of the body joints done during the tennis swing is one of the quantities being assessed in this study. The humanoid model does not evaluate the work of the body joints directly, however it does provides the necessary data to calculate joint work as a post-processing function. Driving the joints of the model kinematically yields the internal reaction forces and driving torques at each joint. Since there is no relative linear motion at the joints, the linear forces do no work, thus from the joint angular kinematics and driving torques, the work done at a joint can be determined from Eqn (A1):

$$Work_{joint} = \int_{t_2}^{t_1} (\vec{\omega}_i \bullet \sum \vec{T}_i) dt \tag{A1}$$

where $\vec{\omega}_i$ *is the relative angular velocity vector,* $\vec{T}_i$ *is the joint torque vector, and i is the alpha (medial/lateral), beta (anterior/posterior), and gamma (long-axis twisting) motion of the joint.*

Using the body 1-2-3 Euler angle representation, the work of a joint can be determined by summing each separate angular movement over time as:

$$Work_{joint} = \sum_0^n T_\alpha(\alpha_{t+\Delta t} - \alpha_t) + \sum_0^n T_\beta(\beta_{t+\Delta t} - \beta_t) + \sum_0^n T_\gamma(\gamma_{t+\Delta t} - \gamma_t) \tag{A2}$$

where n is the number of numerical time steps, $T_\alpha, T_\beta, and T_\gamma$ *are the torque components, t is time, and* Δt *is the time interval of the numerical integrator.*

Since work is a scalar quantity, the work of individual joints can be summed directly to determine the work of a group of joints, or the work of the entire body. These methods have been used to evaluate the work of the body joints of the golfer (Nesbit and Serrano, 2005; Nesbit, 2003b).