ORIGINAL ARTICLE

A descriptive profile of age-specific knee extension flexion strength in elite junior tennis players

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Background: Tennis requires repetitive multidirectional movement patterns that can lead to lower extremity injury. Knowledge of population and age-specific strength parameters can be used during performance enhancement training and rehabilitation of tennis players.
Objectives: The purpose of this study was to generate population and age-specific descriptive profiles of concentric isokinetic knee extension and flexion strength in elite junior tennis players, and determine whether bilateral differences exist between extremities and across age ranges.
Methods: A total of 103 elite male tennis players (mean (SD) 15.92 (2.14), range 11–21) and 53 female tennis players (mean (SD) 15.0 (2.30, range 11–21) were isokinetically tested on a Cybex 6000 isokinetic dynamometer at 180 and 300°/s to assess bilateral concentric knee extension and flexion strength using a standard bilateral testing protocol.
Results: No significant bilateral difference between the dominant (racquet side) lower extremity and the contralateral non-dominant side were measured in lower extremity knee extension or flexion strength normalised to body weight, or in the hamstring quadriceps strength ratios in male and female subjects. Male subjects did show significant ($p<0.001$) increases in knee extension and flexion strength across the age ranges from 11–15 years of age to 16–21 years. Female subjects did not show any significant change in the normalised knee extension or flexion strength across age ranges. Hamstring/quadriceps strength ratios were bilaterally symmetric and remained clinically and statistically constant across age ranges for the male and female elite tennis players.
Conclusions: Population and age-specific isokinetic descriptive data from elite tennis players can provide guidance in the development and monitoring of performance enhancement and rehabilitation programs for elite tennis players. The changes identified in normalised knee extension and flexion strength in elite male tennis players necessitate the use of population and age-specific descriptive data.

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The importance of the lower extremities in tennis has been well described by various researchers[1–3] as a vital link in the kinetic chain principle applicable to virtually all aspects of tennis performance. Initiated by the feet pushing against the ground, all movements in tennis involve the transfer of force and momentum via the kinetic chain segments of the lower extremities to the trunk and, finally, the racquet. The legs contribute to virtually every aspect of tennis performance, from generating the power behind a serve or forehand, to helping a player move around the court. To further illustrate the importance of lower extremity strength and the lower extremity segments, Elliott *et al*[3] measured significant differences between elite level players' serving mechanics based on the amount of "leg drive" (knee flexion and extension) used during their service motion. Players who used greater amounts of knee flexion during the arm-cocking phase of the serving motion had significantly smaller medial elbow and shoulder torques. This finding shows the importance of optimal lower extremity contributions to power generation and protection of other segments in the kinetic chain through its proper contribution.

Musculoskeletal profiling of elite tennis players has identified significantly greater dominant arm strength using isokinetic muscle performance testing.[4–9] Specifically, shoulder internal rotation and extension, elbow extension, forearm pronation and both wrist flexion and extension have all been found to be significantly greater in muscle strength on the dominant arm of elite level players with dynamic isokinetic testing. Similarly, isokinetic testing of trunk strength has identified a specific pattern of strength adaptation in the elite player. Tennis players exhibit greater trunk flexion strength as compared to extension strength.[10] This finding is in direct contrast to that measured in normal subjects,[11] where trunk extension strength exceeds trunk flexion strength. Torso rotation strength has also been tested in male and female elite tennis players, showing relative symmetry between left and right side rotation.[12]

Lower extremity strength testing in the elite tennis player has been less well documented. Ellenbecker and Roetert[13] published a descriptive isokinetic profile reporting composite mean strength ratios across an age range with elite junior tennis players from 11–17 years of age. The results showed bilaterally symmetric knee extension and flexion strength in male and female players at multiple testing speeds. Due to a smaller subject population in that study, age-specific comparisons and analysis of changes between players of differing ages could not be reported.

Assessment of lower extremity strength and muscle balance (agonist/antagonist ratios) is important for injury prevention and performance enhancement. Interest in lower extremity strength and muscle balance, specifically the relationship between the quadriceps and hamstrings, has increased in recent years, in response to literature reporting the increased incidence of anterior cruciate ligament (ACL) injury among adolescent athletes, in particular female athletes, for whom a 2–8-fold increase in ACL injury rate has been reported from a myriad of proposed factors.[14–23] One factor under investigation for increasing female ACL injury risk is that of hamstring/quadriceps muscle balance and the reported difference in the hamstring/quadriceps ratio between male and female athletes during the developmental years.[24 25] Specifically, Barber-Westin *et al*[24] tested 1030 adolescent athletes between the ages of 9–17 using an isokinetic dynamometer at a speed of 300°/s. While the athletes were not specifically tennis players, their sample included adolescent athletes from multi-directional cutting sports like basketball, soccer, football and volleyball. While the investigators found no significant lower limb dominance for knee extension or flexion strength in either the male of female athletes tested, they did find developmental differences in the hamstring quadriceps ratio. Increases in knee extension strength occurred until the age of 13 years in female and 14 years in male subjects, but did not change after that chronological age. Increases were measured in knee flexion peak torque from ages 9–11 in the female subjects and between ages 9–14 the males. Hamstring quadriceps muscle strength ratios decreased from 82% to 70% between ages 10–17 in females, identifying a significant overall change in dynamic muscle balance about the knee joint in these athletes. Hamstring quadriceps ratios in the male subjects also decreased, but only between ages 9–14, with constant ratios remaining between ages 14–17.

Ahmad *et al*,[25] used a handheld dynamometer in 53 male and 70 female soccer players to assess quadriceps and hamstring strength. They found increases in age and maturity did produce significant increases in quadriceps and hamstring strength, however boys demonstrated a greater (179%) hamstring gain compared with girls (27%).

These studies both show differences in strength development in adolescent athletes during a period of growth and development. At present, no sport-specific studies are available on lower extremity strength patterns in elite junior tennis players. The purpose of this study was to generate isokinetic age-specific knee extension/flexion strength profiles for junior tennis players to provide descriptive data for clinicians and scientists, to aid in the interpretation of isokinetic strength tests. A secondary purpose was to determine whether significant differences exist between male and female junior tennis player in knee extension/flexion strength and hamstring/quadriceps strength ratios and across age ranges. Finally, further analysis will test for bilateral differences in these parameters between extremities.

METHODS

Subjects

A total of 103 male and 53 female elite junior tennis players were tested for this study. Subjects had to have sectional, national or international rankings to qualify as an ''elite'' player for this investigation. Subjects were free from any injury in the year prior to testing in either lower extremity or lumbar spine, and with no past history of knee surgery to either extremity. Subjects signed an informed consent prior to participation in this study. The experimental protocol was reviewed and approved by the Institutional Review Board of Physiotherapy Associates.

Instrumentation

The concentric mode of the Cybex 6000 (Cybex Inc., Ronkomkom, New York, USA) isokinetic dynamometer was used for data collection, with calibration of the unit performed according to manufacturer's recommendation.[26]

Procedure

Prior to isokinetic testing, subjects completed a 5 min warm-up on a lower extremity stationary bicycle at a self-selected pace. Following completion of the warm-up, subjects were seated and positioned with a 95° angle between the torso and thigh. They were secured with distal thigh and malleolar straps, and a diagonal and horizontal seat belt. The leg tested first was chosen at random, to minimise the effects of a learning bias. The dominant leg was operationally defined for the purposes of this study as the limb on the same side as the subject's dominant (tennis playing) upper extremity.

Concentric knee extension and flexion strength was tested at speeds of 180 and 300°/s. Speeds were chosen due to their predominance in previously published isokinetic descriptive studies and their use in lower extremity rehabilitation programs.[24 27 28] Testing at each speed consisted of numerous submaximal warm-up repetitions, to allow the subjects to familiarise themselves with the accommodative resistance inherent in isokinetic exercise and testing, followed by three additional submaximal repetitions and finally one maximal repetition of knee extension and flexion immediately prior to actual data collection. This warm-up was used as most subjects had no isokinetic testing or training experience. Testing consisted of five maximal repetitions of knee extension/flexion at both testing speeds and commenced immediately (less than 5 s) following the gradient warm-up sequence at each testing speed. Subjects were tested using a range of motion of 90° of knee extension/flexion. Range of motion stops were utilised to ensure accuracy and consistency of knee range of motion during bilateral testing. Gravity correction was performed using the Cybex 6000 software. Testing was initiated with the knee in flexion, with the initial movement being maximal knee extension. A 30 s rest period was given between test speeds. Following completion of the index extremity, identical procedures and set-up/stabilisation were used to test the contralateral extremity. Test speeds were not randomised, to enhance the reliability of the data acquisition.[29] The test–retest reliability of the concentric mode of the Cybex isokinetic dynamometer has been previously reported as deemed acceptable for musculoskeletal applications.[30]

Data were collected from the five maximal testing repetitions at each testing speed in foot pounds. The normalised variables of peak torque and single repetition work relative to body weight were analysed, using SPSS (SPSS Inc., Chicago, Illinois). Peak torque was the highest point on the torque curve regardless of the location in the range of motion occurring in one of the five testing repetitions. The single repetition work variable used for analysis was the best work repetition of the five sampled (area under the torque curve) occurring during the five testing repetitions.

For the purposes of the descriptive portion of this study, data from both testing speeds and isokinetic variables (peak torque and single repetition work) underwent descriptive analysis, to formulate group means and SD. Data analysis was performed using a repeated measures ANOVA. Variables included in the ANOVA were the single repetition work/body weight ratio and the hamstring/quadriceps single repetition work ratio, both at 300°/s for bilateral lower extremities. A significance level of .05 was used to detect main effect differences for dominance (dominant racquet side lower extremity/non-dominant) motion (knee extension/knee flexion), as well as age (11–15/16–21) and gender (males/females). Post hoc t tests were used where main effect differences were identified. The significance level used for post hoc testing was derived using a Bonferroni correction and set at (.008). A total of six post hoc t tests were used ($0.05/6 = 0.008$) in this investigation and analysis.

RESULTS

A total of 102 male subjects (mean (SD) 15.92 (2.14)), 41 between the ages of 11–15 and 62 between the ages of 16–21 with a mean weight 145.82 pounds, and 53 female subjects (mean (SD) 15.0 (2.37)), 24 between the ages of 11–15 and 29 between the ages of 16–21 with a mean weight of 120.98 pounds, were tested. Age-specific work/body weight ratios for the male and females in both age ranges are displayed in

Table 1 Knee extension/flexion peak torque and work to body weight ratios for male elite junior tennis players age 11–15 (all values expressed as (%) in foot pounds relative to body weight pounds)

Parameter/Speed (n = 41)	Left (non-dominant) Mean	SD	Right (dominant) Mean	SD
Knee extension				
Torque/BW 180	56.6	11.7	57.1	13.2
Torque/BW 300	46.5	7.9	45.6	10.1
Work/BW 180	55.0	12.9	55.2	16.2
Work/BW 300	40.3	10.8	39.6	11.5
Knee flexion				
Torque/BW 180	35.8	9.0	35.2	9.2
Torque/BW 300	30.7	6.8	30.4	7.9
Work/BW 180	35.4	10.5	35.0	10.9
Work/BW 300	24.3	8.8	23.5	9.1

Table 3 Knee extension/flexion peak torque and work to body weight ratios for female elite junior tennis players age 11–15 (all values expressed as (%) in foot pounds relative to body weight pounds)

Parameter/speed (n = 24)	Left (non-dominant) Mean	SD	Right (dominant) Mean	SD
Knee extension				
Torque/BW 180	49.5	10.8	50.2	13.0
Torque/BW 300	39.3	12.7	39.8	13.1
Work/BW 180	50.4	13.6	48.0	14.6
Work/BW 300	35.7	11.7	34.2	12.6
Knee flexion				
Torque/BW 180	30.5	9.6	29.4	8.1
Torque/BW 300	23.7	9.4	24.9	9.1
Work/BW 180	29.6	11.9	29.0	10.4
Work/BW 300	20.5	11.0	21.6	9.7

tables 1–4. Table 5 displays the hamstring/quadriceps ratios at 180 and 300°/s for the male and female elite tennis players.

Comparisons

For the normalised variable of single repetition work/body weight at 300°/s, no significant ($p>0.05$) main effect differences were identified for dominance, indicating no difference between the dominant (racquet side) lower extremity in quadriceps and hamstring strength compared to the non-dominant extremity for male and female subjects, regardless of age.

Significant ($p<0.05$) main effect differences were identified for motion, gender and age (table 6). For the main effect of motion, which compared quadriceps knee extension strength to hamstring strength, as expected, the quadriceps were significantly stronger than corresponding hamstring strength in male and female subjects. For the main effect of gender, male subjects were significantly ($p<0.05$) stronger than their female counterparts when normalised to body weight.

Significant main effect differences were identified for age ($p<0.05$). Post hoc testing using t tests revealed significantly ($p<0.001$) greater knee extension and flexion strength in the 16–21 year olds as compared to the 11–15 year olds in the males, but no significant differences in either knee extension or flexion strength between age groupings in female elite players.

Analysis of the hamstring/quadriceps ratios identified a significant main effect difference for dominance, but no significant difference between genders or across the two age groups of elite players. Post hoc testing for dominant non-dominant differences showed no significant difference ($p = 0.624$) for males and ($p = 0.07$) for females using t tests, indicating no individual group differences in the hamstring/quadriceps ratio in either the male or females.

DISCUSSION

The use of isokinetic testing to objectively measure muscular strength is a common practice in rehabilitation and exercise science. Descriptive studies are necessary to allow for effective and accurate interpretation of the data. This study shows that no significant difference exists between the dominant (racquet side) and non-dominant lower extremity for knee extension or flexion strength in elite junior tennis players. This finding is in agreement with prior isokinetic descriptive studies measuring lower extremity strength in elite tennis players. Ellenbecker and Roetert,[13] using a much smaller subject population of elite players between the ages of 11–17, found bilateral symmetry in knee extension flexion strength, as did Read and Bellamy[31] during testing of 11 elite adult tennis players. This consistent finding allows clinicians and sport scientists to assume bilateral symmetry in lower extremity quadriceps and hamstring function during isokinetic testing following rehabilitation of an injury, or during performance enhancement evaluation. Deficiencies between limbs cannot be assumed to be a result of a dominance effect due to selective muscular development and sport specific adaptation. This is in contrast to findings in the upper extremity of elite level tennis players, where significantly

Table 2 Knee extension/flexion peak torque and work to body weight ratios for male elite junior tennis players age 16–21 (all values expressed as (%) in foot pounds relative to body weight pounds)

Parameter/speed (n = 62)	Left (non-dominant) Mean	SD	Right (dominant) Mean	SD
Knee extension				
Torque/BW 180	66.0	11.4	67.5	10.8
Torque/BW 300	53.3	10.0	53.3	8.8
Work/BW 180	68.8	13.0	70.7	14.0
Work/BW 300	48.1	10.4	49.2	10.7
Knee flexion				
Torque/BW 180	39.6	8.5	41.0	8.0
Torque/BW 300	32.8	6.9	34.1	8.1
Work/BW 180	39.7	9.5	41.8	10.9
Work/BW 300	27.0	7.3	28.5	8.7

Table 4 Knee extension/flexion peak torque and work to body weight ratios for female elite junior tennis players age 16–21 (all values expressed as (%) in foot pounds relative to body weight pounds)

Parameter/Speed (n = 29)	Left (non-dominant) Mean	SD	Right (dominant) Mean	SD
Knee extension				
Torque/BW 180	49.4	11.5	50.8	11.4
Torque/BW 300	41.5	9.7	38.1	9.9
Work/BW 180	48.8	13.4	50.3	14.0
Work/BW 300	35.6	8.2	34.4	9.5
Knee flexion				
Torque/BW 180	30.6	8.9	31.9	6.6
Torque/BW 300	25.5	6.6	25.6	6.8
Work/BW 180	31.7	11.2	33.1	7.5
Work/BW 300	21.7	7.1	21.4	7.2

Table 5 Hamstring/quadricep peak torque and single repetition work ratios for male and female elite junior tennis players age 11–15 and 16–21 years of age (all values expressed as (%) hamstring strength relative to quadriceps strength)

	Age 11–15		Age 16–21	
Parameter/speed	Dominant	Non-dominant	Dominant	Non-dominant
Males				
H/Q PT 180	62 (13)	63 (12)	61 (9)	60 (10)
H/Q PT 300	60 (18)	66 (10)	64 (13)	62 (12)
H/Q Work 180	66 (22)	65 (14)	59 (10)	58 (12)
H/Q Work 300	60 (18)	60 (15)	59 (15)	58 (15)
Females				
H/Q PT 180	59 (14)	59 (20)	63 (8)	62 (12)
H/Q PT 300	64 (21)	61 (18)	65 (11)	61 (4)
H/Q Work 180	61 (19)	59 (20)	67 (11)	65 (15)
H/Q Work 300	63 (27)	56 (24)	63 (13)	60 (13)

Data are mean (SD).

greater concentric dominant shoulder internal rotation, extension/flexion, elbow extension, forearm pronation and wrist extension/flexion strength has been reported in isokinetic descriptive studies.[4–9]

The unique aspect of this study is the use of two separate age divisions or groupings to determine whether changes in muscular strength normalised to the players' body weight occur during growth and development. This study found significant increases in only the elite male players, with no significant change across ages identified in the elite female players. It is unknown at this time why similar changes in muscular strength were not measured in the female subjects. This study provides age-specific data to assist clinicians and researchers in the interpretation of isokinetic tests in elite players during their developing years.

Ahmad *et al*[25] tested 123 adolescent soccer players between the ages of 10–18 years of age and found significant increases in quadriceps and hamstring strength. Strength was measured statically with a handheld dynamometer, but was not normalised to body weight, making a detailed comparison to our study limited. Significant increases were found for males and females, however males showed a greater percent increase specifically in hamstring strength.[25]

Barber-Westin[24] used an isokinetic dynamometer at 300°/s to obtain knee extension/flexion strength normalised to body weight in 1030 athletes 9–17 years of age. Similar to our study, they found increasing normalised strength data for the quadriceps and hamstrings in males, however their study also showed increases in strength up to only age 13 in females. Our study did not find significant increases in normalised quadriceps and hamstring strength, however our age breakdown might have precluded identification of a strength improvement for females, based on the finding of maximal strength improvement occurring by age 13 in Barber-Westin's study.[24] Normalised strength and hamstring quadriceps ratios were not significantly different between the 11–15-year-old females in our study and the 16–21-year-olds we tested. Further study is needed to more fully understand developmental strength patterns in elite tennis players, specifically testing a larger population of young players to allow for comparison between age groups as young as 10–12 and 12–14 years of age.

No significant difference was identified in the hamstring/quadriceps ratio in males or females between age groups in our study. Prior studies[24 25] have identified alterations in this important muscular balance (hamstring/quadriceps) and have theorised that these alterations in muscular balance might increase injury risk. The hamstring/quadriceps peak torque and single repetition work ratios in this study ranged between 58–67% for the speeds of 180 and 300°/s. These ranges can be used to evaluate and monitor elite players during development, as well as to objectively base specific strength and conditioning interventions, in the event hamstring/quadriceps muscular imbalance is encountered. Deviations from the population specific normal muscular strength ratios presented in this study would indicate the need for specific muscular strength training to normalise muscular strength balance. Further research is needed to identify the critical muscle performance values and amount of deviation from these normal ranges whereby an increased injury risk is created.

CONCLUSIONS

Isokinetic testing of knee extension flexion in elite tennis player has identified bilaterally symmetric normalised strength and hamstring/quadriceps ratios in males and females. Age-specific

Table 6 ANOVA results for normalised knee extension and flexion and hamstring/quadriceps ratios

Source	Mean Square	F	Significance
Normalised knee extension flexion			
Dominance	0.830	0.044	0.835
Motion	32 921.42	674.50	0.001*
Gender	6079.85	19.7	0.001*
Age	1369.60	4.44	0.037*
Hamstring/quadriceps ratio			
Dominance	489.04	4.26	0.041*
Gender	217.17	0.382	0.538
Age	4.77	0.008	0.927

* Denotes Significance at the $p = 0.05$ level.

What is known on this topic

Prior research has identified symmetric lower extremity quadriceps and hamstring strength in elite tennis players.

What this study adds

- Prior studies identifying symmetrical lower extremity muscular performance are confirmed.
- Age-specific descriptive data for male and female elite tennis players is provided.

normalised data are provided, due to the finding of significantly greater knee extension and flexion strength in the 16–21-year-old male players as compared to the 11–15-year-old players. No significant difference between age groups was measured for normalised strength in the elite female players. No significant difference was found in hamstring/quadriceps muscular strength ratios between the male and female elite player or between age groups. Descriptive data presented in this study can assist clinicians and researchers in the interpretation of lower extremity isokinetic muscle performance tests during rehabilitation or performance enhancement evaluations.

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