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Adaptive Alterations in Shoulder Range of Motion and Strength in Young Tennis Players

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Context: Playing tennis requires unilateral and intensive movement of the upper limb, which may lead to functional adaptations of the shoulder and an increased injury risk. Identifying which athletes will be future elite tennis players starts at 5 to 6 years of age. Therefore, highly skilled players practice intensively in their childhood. However, whether these functional changes occur during the prepubertal years has not been established.

Objectives: To assess changes in glenohumeral-joint–rotation range of motion and strength of the shoulder-complex muscles in prepubertal elite tennis players.

Design: Cross-sectional study.

Setting: Tennis training sports facilities.

Patients or Other Participants: Sixty-seven male tennis players (age range = 7–13 years) selected by a regional tennis center of excellence were divided into 3 biological age groups relative to their predicted age at peak height velocity: greater than 4 (n = 26; age = 8.7 ± 0.7 years, height = 132.4 ± 12.9 cm, mass = 27.8 ± 3.8 kg), 3 to 4 (n = 21; age = 10.3 ± 0.6 years, height = 144.9 ± 5.7 cm, mass = 34.7 ± 4.0 kg), and 2 (n = 20; age = 12.8 ± 1.4 years, height = 158.5 ± 8.7 cm, mass = 43.0 ± 8.2 kg) years before their age at peak height velocity.

Main Outcome Measures(s): We measured the internal- and external-rotation ranges of motion of the glenohumeral joint using a goniometer and calculated the total arc of motion. Maximal isometric strength of 8 shoulder muscles was measured using a handheld dynamometer. Strength values were normalized to body weight and used to calculate 4 agonist-to-antagonist strength ratios.

Results: The total arc of motion of the glenohumeral joint decreased gradually with biological age ($P \leq .01$) due to the decrease in internal-rotation range of motion ($P < .001$). Absolute strength increased gradually with biological age ($P < .001$), but the relative strengths and ratios remained similar.

Conclusions: Functional adaptations of the shoulder seen in adolescent and adult tennis players were observed in healthy prepubertal players. This knowledge could help clinicians and coaches more effectively monitor shoulder adaptations to tennis practice during the prepubertal years.

Key Words: scapular muscles, glenohumeral joint, internal rotation, children, overhead throwing athletes

Key Points

- Internal-rotation range of motion (ROM) decreased with increasing biological age, likely due to tennis practice.
- Given that the increased external ROM of the dominant glenohumeral joint did not fully compensate for the decreased internal-rotation ROM, total arc of motion was less on the dominant than on the nondominant side for all groups.
- The dominant side was stronger than the nondominant side for all biological ages.
- The agonist-to-antagonist strength balance was similar between asymptomatic dominant and nondominant shoulders and among the biological age groups.
- Clinicians and coaches should monitor shoulder adaptations to tennis practice during the prepubertal years to prevent inappropriate adaptations in these young overhead-throwing athletes.

The different tennis strokes, specifically the serve, apply high loads to the shoulder complex,[1] leading to an increased risk for shoulder pain. In adolescent and adult overhead athletes, chronic shoulder pain is often associated with glenohumeral internal-rotation deficit,[2] rotator cuff weakness,[3] and scapular dyskinesia.[4] The major risk factor for these overuse injuries is high training volume.[5] Highly skilled tennis players commonly start to practice intensively at an early age. For example, the French Federation recommends that future elite players should begin to be scouted at 5 to 6 years of age.[6] Nevertheless, few researchers have studied the first years of intensive practice.

The unilateral, forceful, and repetitive nature of tennis results in sport-specific adaptations on the dominant side, especially at the shoulder complex. Alterations in range of motion (ROM) and strength have been documented in both adolescent[7–10] and adult tennis players.[8,11,12] Researchers[11] have consistently reported a gradual decrease in internal-rotation ROM (IROM) of the dominant glenohumeral joint with increasing age and years of tennis practice. In addition, some investigators[8,13] have reported increased glenohumeral external-rotation ROM (EROM) of the dominant side, whereas others[14,15] have observed no change. The alterations in maximum strength of the shoulder complex have been extensively characterized by the strength ratio between the internal-rotator (IR) and external-rotator (ER) muscles.[9,15,16] On the dominant side, with practice, IR strength increases more than ER strength, resulting in an unbalanced shoulder function profile. In addition to reporting scapular positioning and motion alterations in tennis players,[17,18] researchers have assessed scapular muscle strength. Cools et al[7] observed that adolescent players had greater strength on the dominant than on the nondominant side for the shoulder-elevator and the scapular IR and upward-rotator muscles but no bilateral differences for scapular external- or posterior-rotator muscle strength. All of these tennis-specific adaptations have been shown in both adolescent and adult populations. However, to the best of our knowledge, functional changes occurring at the shoulder joint during the prepubertal years have not been documented.

When compared with chronologic age, young players' shoulder-muscle strength gradually increases with both age and mass, except for the dominant IR and upper trapezius muscles.[8] However, grouping prepubertal boys by chronologic age may bias the analysis.[19,20] Indeed, a large amount of variability in biological and somatic growth exists for a given chronologic age, which could be an advantage or a disadvantage for some children in fitness tests, especially strength assessment.[20] In young boys, increased strength is related to increased mass and height and to increased levels of androgens, particularly testosterone.[20] Consequently, grouping young athletes based on their biological age seems to provide a better-controlled condition.[21,22] The standard methods used to evaluate biological age are the assessments of skeletal age, dental age, and secondary sex characteristics.[23] The evaluation of skeletal or dental age requires radiographic equipment, whereas the secondary sex characteristics are assessed through direct visual observation.[23] Such methods are intrusive and hard to apply in sports facilities.[24] Somatic methods based on body proportions combined with chronologic age offer a nonintrusive and convenient alternative. One method is the equation of Mirwald et al,[25] which estimates the number of years to attain the predicted age at peak height velocity (APHV). Maturation classification based on APHV may be a way to assess changes in the shoulder complex over time in young tennis players.

Therefore, the purpose of our study was to investigate adaptations in shoulder ROM and strength in prepubertal, healthy male competitive tennis players according to their biological age. After considering shoulder-complex alterations in adult and adolescent tennis players, we hypothesized that we would observe decreased IROM and increased EROM of the dominant shoulder compared with the nondominant shoulder and that these bilateral differences would be accentuated as biological age increased; the absolute strength of the shoulder and scapular muscles would be greater on the dominant than the nondominant side and should increase gradually with biological age; and normalized strength would be greater for the dominant side but would not change with increasing biological age.

METHODS

Participants

Sixty-seven healthy boys (age = 10.4 ± 1.9 years [range = 7–13 years], height = 144.1 ± 12.9 cm [range = 115.5–179.0 cm], mass = 34.5 ± 8.3 kg [range = 27–43 kg]) practicing competitive tennis volunteered to participate in this study. All participants and their legal guardians provided written informed assent and consent, respectively, and the study was approved by the Ethics Committee Sud-Est II (Institutional Review Board 0009118). Participants, who were recognized as elite players in their age categories, were members of a regional tennis center of excellence (Lyon, France). No player had a history of shoulder injury or practiced another sport activity.

Players supplied their tennis characteristics, including years of tennis practice, weekly tennis and conditioning exposure, type of backhand, and ranking. French qualitative ranking[26] was transformed into a quantitative variable as proposed by Lac and Pantelidis,[27] with 0 corresponding to *no ranking*; 1, *ranking 40*; 2, *ranking 30/5*; and so on. Players' standing height, sitting height, and body mass were measured and used with the chronologic age to estimate their biological age relative to their APHV according to the equation of Mirwald et al.[25] Players were divided into 3 groups according to their biological age: players who were more than 4 years from their predicted APHV (APHV-4; n = 26), between 3 and 4 years from their APHV (APHV-3; n = 21), and around 2 years from their APHV (APHV-2; n = 20; Table 1).

Measurement Protocol

The study design consisted of 2 types of bilateral measures: glenohumeral-rotation ROM and the maximal isometric strength of the shoulder-complex muscles. To estimate the intrarater reliability, each series of measures was taken twice by the same experienced examiner (B.G.). Before measurements, all players warmed up with rallies in the service boxes.

Glenohumeral ROM. Passive IROM and EROM of the glenohumeral joint were assessed bilaterally using a 12-in (30.5-cm) plastic bubble goniometer (model Baseline Absolute+Axis; Fabrication Enterprises, Inc, White Plains, NY). The player lay supine with the humerus abducted to 90° and elbow flexed to 90°. The fulcrum of the goniometer was set at the olecranon process. The branch with the bubble was placed vertically, and the other branch followed the styloid process of the ulna. To evaluate only glenohumeral ROM, the examiner palpated the coracoid process with his thumb and the scapular spine with the other fingers to prevent scapula movement.[28] Next, he moved the player's humerus to the maximal passive IROM and EROM while another examiner (V.S. or I.R.) set the goniometer and read the value. The mean value was used for statistical analysis and to calculate the total arc of motion (TAM = IROM + EROM) and side-to-side asymmetry in IROM (dominant − nondominant). The

Table 1. Demographic and Tennis Characteristics by Group Controlled for Biological Age

Characteristic	APHV Group		
	4[a] (n = 26)	3[b] (n = 21)	2[c] (n = 20)
Age, y, mean ± SD	8.7 ± 0.7[d,e]	10.3 ± 0.6[f]	12.8 ± 1.4
Height, m, mean ± SD	132.4 ± 12.9[d,e]	144.9 ± 5.7[f]	158.5 ± 8.7
Mass, kg, mean ± SD	27.8 ± 3.8[d,e]	34.7 ± 4.0[f]	43.0 ± 8.2
APHV, y, mean ± SD	−4.6 ± 0.5[d,e]	−3.5 ± 0.3[f]	−1.7 ± 1.0
Tennis starting age, y, mean ± SD	4.8 ± 1.0	5.1 ± 1.3	4.6 ± 1.0
Tennis practice, y, mean ± SD	4.1 ± 1.1[d,e]	5.2 ± 1.5[g]	9.0 ± 1.8
Weekly tennis exposure, h, mean ± SD	6.5 ± 2.3[h,i]	8.1 ± 2.4	9.2 ± 2.1
Weekly conditioning exposure, h, mean ± SD	1.1 ± 1.2[e]	1.5 ± 1.1[j]	3.4 ± 1.8
Ranking, mean ± SD	0.7 ± 1.5[d,e]	4.8 ± 3.0[f]	12.6 ± 2.3
Laterality, left/right	3/23	1/20	1/19
Backhand, 1 hand/2 hands	4/22	3/18	3/17

Abbreviation: APHV, age at peak height velocity.

[a] APHV-4 consisted of players who were more than 4 years from their APHV.
[b] APHV-3 consisted of players who were between 3 and 4 years from their APHV.
[c] APHV-2 consisted of players who were close to 2 years from their APHV.
[d] Difference between APHV-4 and APHV-3 groups ($P \leq .001$).
[e] Difference between APHV-4 and APHV-2 groups ($P \leq .001$).
[f] Difference between APHV-3 and APHV-2 groups ($P \leq .001$).
[g] Difference between APHV-3 and APHV-2 groups ($P \leq .05$).
[h] Difference between APHV-4 and APHV-3 groups ($P \leq .05$).
[i] Difference between APHV-4 and APHV-2 groups ($P \leq .01$).
[j] Difference between APHV-3 and APHV-2 groups ($P \leq .01$).

intraclass correlation coefficients (ICC [2,k])[29] and the standard error of measurement (SEM) ranged from 0.81 to 0.87 and 0.82° to 1.26°, respectively, indicating good intrarater reliability.

Isometric Strength. The maximal isometric strength of 8 shoulder-complex muscles was assessed bilaterally using a handheld dynamometer (model microFET2; Hoggan Health Industries Inc, West Jordan, UT), as described in previous studies,[7,15] and summarized in Table 2. Each test was performed twice, with a 30-second rest period between tests.[15] The largest strength value for each muscle was used for statistical analyses, normalized to body weight (in newtons), and expressed as a percentage for interindividual comparison.[30] Finally, we calculated 4 strength ratios, including ERs to IRs, upper to lower trapezius, upper trapezius to latissimus dorsi, and middle trapezius to serratus anterior used in previous studies.[7,9] The intrarater reliability of force measurement was good (ICC [2,k] range = 0.81–0.95; SEM range = 0.75–6.33 N).

Statistical Analysis

After testing for normality and homoscedasticity of the values, we compared demographic and tennis characteristics using analyses of variance (ANOVAs) with 1 between-subjects factor (biological age: APHV-4, APHV-3, or APHV-2). When we observed a difference, we applied a post hoc Tukey test to compare the 3 groups. For ROM and strength outcomes, ANOVAs with 1 between-subjects factor (biological age) and 1 within-subject factor (lateral-

Table 2. Description of the Player Positions for Testing Shoulder-Complex Muscle Strength Against Examiner Resistance

Muscle(s)	Player Position	Handheld Dynamometer Position	Exertion
Internal rotators[15]	Supine position, humerus abducted to 90°, elbow flexed to 90°	Ventral and proximal ulnar styloid process	Internal rotation
External rotators[15]	Supine position, humerus abducted to 90°, elbow flexed to 90°	Dorsal and proximal distal ulnar styloid process	External rotation
Serratus anterior[7]	Supine position, humerus forward flexed to 90°, elbow extended	Palm hand	Protraction
Upper trapezius[7]	Sitting position with upper extremity beside the body with elbow maximally extended	Upper border of the acromion	Shoulder elevation
Middle trapezius[7]	Prone position, humerus abducted to 90°and fully externally rotated, elbow maximally extended	Lateral aspect of the distal radius	Horizontal abduction
Lower trapezius[7]	Prone position, humerus abducted to 145° and maximally externally rotated, elbow maximally extended	Lateral aspect of the distal radius	Horizontal abduction
Latissimus dorsi[7]	Prone position, humerus abducted to 45° and maximally externally rotated, elbow fully extended	Lateral side of the wrist	Horizontal abduction
Rhomboid[7]	Prone position, upper extremity in back, elbow flexed to 90°, head oriented to opposite side of extremity in back	Upper border of the scapula	Retract shoulder

Table 3. Motion of the Dominant and Nondominant Glenohumeral Joint by Biological Age

Motion, °	Side	APHV Group, Mean ± SD		
		4[a]	3[b]	2[c]
Internal range of motion	Dominant	78 ± 9[d,e]	69 ± 9	66 ± 9
	Nondominant[f]	81 ± 9	76 ± 9	74 ± 11
External range of motion	Dominant	84 ± 9	85 ± 10	83 ± 10
	Nondominant[g]	83 ± 6	83 ± 11	79 ± 12
Total arc of motion	Dominant	161 ± 13[h]	153 ± 15	149 ± 16
	Nondominant[f]	163 ± 13	158 ± 15	154 ± 17
Internal range of motion side-to-side asymmetry		5 ± 11	8 ± 9	8 ± 10

Abbreviation: APHV, age at peak height velocity.

[a] APHV-4 consisted of players who were more than 4 years from their APHV.
[b] APHV-3 consisted of players who were between 3 and 4 years from their APHV.
[c] APHV-2 consisted of players who were close to 2 years from their APHV.
[d] Difference between APHV-4 and APHV-3 groups ($P \leq .01$).
[e] Difference between APHV-4 and APHV-2 groups ($P \leq .001$).
[f] Bilateral difference ($P \leq .001$).
[g] Bilateral difference ($P \leq .05$).
[h] Difference between groups APHV-4 and APHV-2 ($P \leq .01$).

ity: dominant versus nondominant side) were performed. When an interaction effect was found, post hoc Tukey and *t* tests were applied. When ANOVA revealed a biological age effect, post hoc Tukey tests were also used. In both cases, we applied a Bonferroni correction. All statistical analyses were performed using SPSS (version 11.0; SPSS Inc, Chicago, IL). The α level was set at .05.

RESULTS

The ANOVAs revealed effects of biological age for chronologic age, height, mass, age from APHV, tennis practice, weekly tennis exposure, weekly conditioning exposure, and ranking (F range 7.58–153.05, all $P \leq .05$; Table 1). We observed no effect for tennis starting age, laterality, or type of backhand.

Chronologic age, height, mass, years of tennis practice, and APHV increased over all 3 biological age groups (Table 1). The average ranking of boys in the APHV-4, APHV-3, and APHV-2 groups corresponded to the French rankings of 40, 30/2, and 15, respectively. Participants in the APHV-2 and APHV-3 groups displayed similar weekly tennis hours but trained longer than those in the APHV-4 group. Boys in the APHV-2 group participated in more weekly conditioning hours than those in the APHV-3 and APHV-4 groups.

For glenohumeral-joint ROM, we observed no interaction effect but did note effects of both biological age and laterality for IROM ($F_{2,64} = 7.93$, $P < .001$, and $F_{1,64} = 28.40$, $P < .001$, respectively) and TAM ($F_{2,64} = 3.78$, $P = .01$, and $F_{1,64} = 9.58$, $P = .001$, respectively; Table 3). The IROM was less on the dominant than on the nondominant side. Moreover, the IROM was lower in boys in the APHV-2 ($P = .001$) and APHV-3 ($P = .007$) groups than in those in the APHV-4 group. The TAM was lower for the dominant than for the nondominant shoulder and lower for boys in the APHV-2 group than in the APHV-4 group ($P = .01$). A laterality effect ($F_{1,64} = 3.78$, $P = .03$) was evident for EROM, with the dominant side being greater than the nondominant side. Finally, we found no effect for side-to-side asymmetry in IROM ($F_{2,64} = 1.94$, $P = .15$).

For absolute strength values (Table 4), no interaction effect was present, but an effect of laterality occurred for IRs ($F_{1,64} = 14.57$, $P < .001$), ERs ($F_{1,64} = 8.94$, $P = .002$), latissimus dorsi ($F_{1,64} = 9.39$, $P = .002$), middle trapezius ($F_{1,64} = 7.82$, $P = .004$), and lower trapezius ($F_{1,64} = 10.76$, $P = .001$) with greater strength on the dominant than on the nondominant side (Table 4). We also observed an effect of biological age for all the investigated muscles (F range = 10.63–36.62, all P values $< .001$). Post hoc analyses of the biological age effect revealed that strengths were higher in the APHV-2 group than in both the APHV-3 and APHV-4 groups for the upper trapezius ($P < .001$ for both), IRs ($P = .001$ and $P < .001$, respectively), ERs ($P = .002$ and $P < .001$, respectively), serratus anterior ($P < .001$ for both), latissimus dorsi ($P = .03$ and $P < .001$, respectively), middle trapezius ($P = .01$ and $P < .001$, respectively), lower trapezius ($P < .001$ for both), and rhomboids ($P = .001$ and $P < .001$, respectively) muscles. Post hoc analyses also showed that ERs and middle trapezius muscles were stronger in the APHV-3 group than in the APHV-4 group ($P = .05$ and $P = .02$, respectively). When strengths were normalized to body weight (Table 4), a laterality effect was observed for the IRs ($F_{1,64} = 13.38$, $P < .001$), ERs ($F_{1,64} = 5.65$, $P = .01$), latissimus dorsi ($F_{1,64} = 7.67$, $P = .005$), middle trapezius ($F_{1,64} = 6.75$, $P = .005$), and lower trapezius ($F_{1,64} = 6.91$, $P = .007$) muscles. The normalized strength was greater on the dominant than on the nondominant side. Nevertheless, no effect was observed for the upper trapezius, serratus anterior, or rhomboid muscles (F range = 0.49–1.94, P values $> .05$). We noted no difference in strength ratios (F range = 0.34–2.83, P values $> .05$; Table 5).

DISCUSSION

We assessed the changes in glenohumeral internal and external rotation and muscular isometric strength of the shoulder complex in prepubertal tennis players according to their biological age. Our main findings highlighted the decreased TAM with biological age due to reduced IROM. The strength of the shoulder and scapular muscles increased with biological age and was greater for the dominant shoulder except for the upper trapezius, serratus anterior, and rhomboid muscles. When strength values were expressed relative to body weight, only bilateral differences remained.

Table 4. **Absolute and Normalized Strength of the Shoulder and Scapular Muscles of the Dominant and Nondominant Sides by Biological Age, Mean ± SD**

		Absolute Strength, N			Normalized Strength, %		
Muscle(s)	Side	APHV-4[a]	APHV-3[b]	APHV-2[c]	APHV-4[a]	APHV-3[b]	APHV-2[c]
Upper trapezius	Dominant	198 ± 28[d]	224 ± 41[e]	300 ± 73	73 ± 9	67 ± 16	72 ± 15
	Nondominant	196 ± 36	216 ± 31	287 ± 54	72 ± 12	65 ± 13	69 ± 13
Internal rotators	Dominant	91 ± 19[d]	101 ± 21[e]	134 ± 38	34 ± 7	30 ± 7	32 ± 6
	Nondominant[f,g]	85 ± 20	99 ± 17	123 ± 42	31 ± 7	30 ± 7	29 ± 7
External rotators	Dominant	81 ± 15[d,h]	93 ± 19[i]	120 ± 33	31 ± 5	29 ± 5	29 ± 7
	Nondominant[j,k]	80 ± 15	93 ± 19	113 ± 31	30 ± 6	28 ± 7	27 ± 6
Serratus anterior	Dominant	162 ± 44[d]	192 ± 24[e]	271 ± 52	61 ± 14	58 ± 9	63 ± 9
	Nondominant	174 ± 40	191 ± 35	250 ± 62	65 ± 12	58 ± 12	59 ± 15
Latissimus dorsi	Dominant	43 ± 10[d]	52 ± 8[l]	66 ± 19	16 ± 3	16 ± 3	15 ± 4
	Nondominant[j,k]	40 ± 10	49 ± 10	57 ± 18	15 ± 3	15 ± 4	13 ± 2
Middle trapezius	Dominant	30 ± 6[d,h]	39 ± 9[l]	53 ± 15	11 ± 3	12 ± 3	12 ± 4
	Nondominant[j,k]	29 ± 7	37 ± 9	43 ± 11	11 ± 3	11 ± 3	10 ± 2
Lower trapezius	Dominant	27 ± 8[d]	29 ± 5[e]	42 ± 9	10 ± 3	9 ± 2	10 ± 2
	Nondominant[f,j]	25 ± 6	26 ± 6	36 ± 7	9 ± 2	8 ± 2	8 ± 2
Rhomboids	Dominant	125 ± 23[d]	146 ± 27[i]	173 ± 45	46 ± 9	44 ± 11	41 ± 9
	Nondominant	125 ± 26	138 ± 23	178 ± 45	46 ± 9	41 ± 10	42 ± 9

Abbreviation: APHV, age at peak height velocity.

[a] APHV-4 consisted of players who were more than 4 years from their APHV.
[b] APHV-3 consisted of players who were between 3 and 4 years from their APHV.
[c] APHV-2 consisted of players who were close to 2 years from their APHV.
[d] Difference between APHV-4 and APHV-2 groups ($P \leq .001$).
[e] Difference between APHV-3 and APHV-2 groups ($P \leq .001$).
[f] Bilateral difference for absolute strength ($P \leq .001$).
[g] Bilateral difference for normalized strength ($P \leq .001$).
[h] Difference between APHV-4 and APHV-3 groups ($P \leq .05$).
[i] Difference between APHV-3 and APHV-2 groups ($P \leq .01$).
[j] Bilateral difference for normalized strength ($P \leq .01$).
[k] Difference between APHV-3 and APHV-2 groups ($P \leq .05$).
[l] Bilateral difference for absolute strength ($P \leq .01$).

Biological Age and Laterality: 2 Efficient Measures to Compare Prepubertal Players

Large interindividual variability was found in young athletes of the same chronologic age due to timing and tempo variations in maturity processes.[23,31] We grouped players according to their biological age rather than their chronologic age. Given that all players had started tennis practice at a similar chronologic age (Table 1), the biological age groups differed for anthropometry and the number of years of tennis practice. Consequently, the strength and ROM alterations observed among groups may be explained by the increase in both the biological age and training-load accumulation. Given that the weekly tennis exposure of the APHV-2 and APHV-3 groups was similar to that of Dutch[32] (age range = 11–14 years) and Swedish[8] (age <14 years) elite players, the findings may be generalized to young elite tennis players. In addition, previous comparisons between tennis and soccer players, as well as with inactive individuals, have shown that tennis practice generates larger alterations in the dominant upper limbs than does biological age.[33,34] Furthermore, the tennis players' nondominant upper extremity remained similar to the control players' nondominant upper extremity.[33,34] Given its unilateral nature, tennis activity offers an interesting model for studying the adaptations of the dominant upper extremity to physical stress, using the nondominant upper extremity as a control. Researchers

Table 5. **Strength Ratios of the Shoulder and Scapular Muscles of the Dominant and Nondominant Sides by Biological Age, Mean ± SD**

		APHV Group		
Muscles	Side	4[a]	3[b]	2[c]
External/internal rotators	Dominant	0.93 ± 0.17	0.97 ± 0.15	0.91 ± 0.16
	Nondominant	0.97 ± 0.16	0.95 ± 0.13	0.95 ± 0.11
Upper/lower trapezius	Dominant	7.65 ± 2.05	7.61 ± 1.36	7.98 ± 2.48
	Nondominant	7.99 ± 2.03	8.49 ± 1.94	8.60 ± 1.80
Upper trapezius/latissimus dorsi	Dominant	4.66 ± 0.87	4.25 ± 0.60	4.88 ± 0.94
	Nondominant	4.95 ± 1.70	4.48 ± 0.79	5.56 ± 1.47
Middle trapezius/serratus anterior	Dominant	0.20 ± 0.05	0.21 ± 0.05	0.20 ± 0.06
	Nondominant	0.17 ± 0.06	0.20 ± 0.06	0.18 ± 0.04

Abbreviation: APHV, age at peak height velocity.

[a] APHV-4 consisted of players who were more than 4 years from their APHV.
[b] APHV-3 consisted of players who were between 3 and 4 years from their APHV.
[c] APHV-2 consisted of players who were close to 2 years from their APHV.

commonly recognize that bilateral comparison eliminates the confounding effects of genetic, hormonal, and nutritional factors in cross-sectional studies.[35,36] Bilateral comparison also offers an alternative approach to including a control group to investigate the effects of tennis practice on dominant upper extremity adaptations. The strength and ROM alterations in the dominant extremity among groups that we observed would most likely be due to tennis practice.

Glenohumeral Range of Motion

The dominant glenohumeral joint of healthy adolescent and adult tennis players is characterized by a decrease in IROM.[2] We also showed that deficits in IROM of the dominant glenohumeral joint occurred before APHV (ie, before adolescence). The deficits appeared between 4 and 3 years before the predicted APHV.

Given that more mature players had a greater amount of tennis practice, these alterations may be related to soft tissue restrictions resulting from repetitive stress applied to the shoulder during tennis strokes.[7] The expected decrease in dominant IROM between the APHV-3 and APHV-2 groups was not observed. These groups had similar tennis exposure, which may explain the absence of difference in IROM. Therefore, the decrease in IROM on the dominant side was probably due to the tennis practice and not the increase in biological age. Researchers have shown that side-to-side asymmetry in IROM between 18° and 25°, as a glenohumeral internal-rotation deficit,[37] places the overhead-throwing athlete's shoulder at high risk for injury.[11] Our values (5°–8°) remained lower than the values indicating injury risk. Therefore, whereas adaptations in ROM of the dominant glenohumeral joint may occur early in a tennis player's career, these alterations do not increase the injury risk at this stage.

In parallel, EROM was higher on the dominant than on the nondominant side, but this bilateral difference was similar across the 3 groups. Increased EROM is reported to be primarily caused by osseous modeling of the immature skeleton, especially humeral retroversion.[28] Observing these changes in prepubertal elite players seems logical because the immature skeleton is better able to remodel and presents greater ligamentous laxity than a mature one.[38] The immature skeleton is characterized by greater bone plasticity as well as a greater capacity to absorb energy.[38] Therefore, the large external-rotation moment of the glenohumeral joint involved in repeated tennis strokes leads to bone adaptations with humeral retroversion and may explain the observed EROM bilateral differences.[28] The lack of increased EROM in our biological age groups may be associated with the chronologic ages of our players. Levine et al[39] showed that this bony adaptation occurs mainly between the ages of 13 and 16 years, whereas our players ranged in age from 8 to 13 years. This increase in EROM may also be related to the elongation of the anterior band of the inferior glenohumeral ligament due to the forced external rotation beyond the normal limits of passive external rotation.[40] Ligamentous laxity is a characteristic of prepubertal elite players.[38] This adaptation, therefore, may occur later in an overhead athlete's career and may not be responsible for the observed increase in EROM. However, this increased EROM did not fully compensate for the decreased IROM, resulting in a TAM deficit on the dominant compared with the nondominant side for all groups. Such a compensatory mechanism enables greater angular velocity during the acceleration phase of overhead throwing and has been primarily observed in baseball players.[28] Whereas a larger EROM may contribute to an improved tennis serve,[10] the mechanical advantage offered by the racket through its lever arm may minimize the importance of increased EROM in generating greater velocity.[15]

Given our results that included a decrease in IROM and a lack of increase in EROM across biological age groups and the findings of Levine et al[39] on EROM adaptations, we suggest that changes in IROM may predominate over changes in EROM during the prepubertal years. Finally, the ROM alterations observed in adolescent and adult tennis players due to tennis practice were also observed in young players.

Maximal Isometric Strength of the Shoulder-Complex Muscles

In adolescent players (aged 13 to 17 years), the absolute isometric strength of the shoulder-complex muscles increases on both sides as chronologic age increases.[8] Whereas we divided the prepubertal players into 3 groups according to their biological age, our findings highlighted that this increase in strength was pre-existing. Specifically, tennis players already presented a stronger dominant than nondominant upper limb.[41] In our study, similar results, with differences up to 23%, were found for the IRs, ERs, latissimus dorsi, middle trapezius, and lower trapezius muscles. This asymmetry could be attributed mainly to the repetitive unilateral muscular exertion required for tennis movements beginning in the first years of intensive practice, as the conditioning program of our population focused on strengthening and stretching both upper limbs. However, in contrast to previous research in older players,[7,8] the upper trapezius and serratus anterior muscles displayed similar bilateral strength, which should be discussed. According to Cools et al,[7,8] these muscles were stronger on the dominant side, probably due to their role in the tennis-stroke motion. During the tennis serve, the upper trapezius contributes to shoulder elevation, whereas the serratus anterior muscle acts concentrically to posteriorly tilt and upwardly rotate the scapula during the cocking and acceleration phases.[1,42] In children, the major contributor to upper extremity elevation is scapular upward rotation.[43] This alternative motion may lead to less use of the upper trapezius and may explain the absence of the expected bilateral difference for this muscle. Furthermore, serve performance correlates with tennis-player height.[44] Given their limited body height, prepubertal players may not be able to hit powerful flat serves,[45] hence limiting strength development of the dominant serratus anterior muscle. In overhead athletes, rhomboid strength is similar on both sides.[46] Our study highlighted similar results. The rhomboid strength was symmetrical, probably because its main function is to maintain the medial border of the scapula on the thoracic wall with a small contribution in the scapular external-rotation motion. Similar to adolescent and adult tennis players, prepubertal players presented stronger muscles in the dominant upper limbs except for the upper trapezius, serratus anterior, and rhomboid muscles.

Normalized strength is the expression of absolute strength relative to body weight. For adolescent players grouped according to chronologic age, Cools et al[8] reported that normalized strength of the shoulder-complex muscles, except for the upper trapezius and IRs, remained similar through adolescence. Our results, with prepubertal players grouped according to biological age, were different; all normalized strength of the shoulder-complex muscles remained similar across biological age groups. Jones et al[20] observed that muscular strength increased progressively with both mass and height. Finding no difference in normalized strength as biological age increased seems logical. Furthermore, the bilateral strength differences in the IRs, ERs, middle trapezius, lower trapezius, and latissimus dorsi were maintained after normalization. These differences undoubtedly resulted from the repeated unilateral muscular exertion required for tennis motions. The bilateral differences observed in all of our biological groups, along with the lack of normalized strength differences among groups, emphasizes that the strength alterations observed during the prepubertal period may be due to intensive tennis practice.

Tennis practice creates an imbalance between the mobilizer and stabilizer muscles.[7,9] The ratio between the ERs and IRs has been extensively described in the literature, with the glenohumeral IRs being stronger than the ERs.[9,16] Furthermore, an imbalance between the agonist and antagonist muscles of the scapula is a risk factor for developing a shoulder injury.[4,16] Our players were healthy and presented no bilateral differences in strength ratios. The lack of difference in their strength ratios may reinforce the importance of developing the dominant side in symmetric proportion to the nondominant side to preserve physical integrity.[47] From an early age, a strength balance in the dominant rotator cuff and scapular muscles is crucial to maintaining humeral head congruence in the glenoid cavity when the upper extremity carries out tennis movements.

Limitations

Our study had limitations. A first limitation lies in the sample of players: elite male players from 7 to 13 years old. However, our results, which complement those of Cools et al,[8] who studied 13- to 17-year-old elite male players, cannot be generalized to tennis players of other skill levels, sexes, or ages. A second limitation may concern the method used to normalize the strength values. We expressed strength values relative to body weight,[7,8,30] whereas other methods, such as the allometric method,[48] can offer a reliable alternative. Furthermore, measuring isometric torque instead of force may reduce uncertainties due to sensor position and interparticipant variability in body-segment lengths. A third limitation comes from choosing an isometric contraction mode for the strength measurements. The isometric contraction might not reflect the actions of the shoulder and scapular muscles involved in tennis practice, which mainly requires concentric and eccentric contractions[16] up to 2000°/s at the glenohumeral joint.[49] Isokinetic measurements may be more appropriate but take more time, and an isokinetic dynamometer was not available in our tennis training facilities. However, we are the first to focus on shoulder ROM and strength in prepubertal players involved in intensive tennis practice. Our results contribute to the description of the adaptive mechanisms in shoulder ROM and strength in healthy male tennis players during APHV. Studies are needed to compare the ROM and strength adaptations between healthy and painful shoulders in young tennis players to provide useful information for shoulder rehabilitation.

CONCLUSIONS

In healthy, prepubertal, elite male tennis players, IROM decreased in relation to biological age and was not compensated for by increased EROM, thus, resulting in decreased TAM of the dominant side compared with the nondominant side. Overall, the dominant side was stronger than the nondominant side for all biological ages. We also observed that an asymptomatic dominant shoulder display an agonist-to-antagonist strength balance similar to that of the nondominant shoulder. These findings indicate that tennis-specific adaptations at the shoulder joint occurred early in childhood. We present new information to clinicians and coaches to improve the monitoring of shoulder adaptations to tennis practice during the prepubertal years and to prevent inappropriate adaptations of the shoulder in young, overhead-throwing athletes.

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