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A low carrying angle is measured in elite tennis players just before ball impact during the forehand, suggesting a dynamic varus instant accommodation moving towards full extension

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Abstract

Purpose: The goal of this study was to use image analysis recordings to measure the carrying angle of elite male tennis players during the forehand stroke, with the hypothesis that elite tennis players overstress their elbow in valgus over the physiological degree in the frontal plane just before ball contact on forehand groundstrokes.

Methods: The carrying angle of male tennis players ranked in the top 25 positions in the ATP ranking was measured on selected video frames with the elbow as close as possible to full extension just before the ball-racket contact in forehands. These frames were extracted from 306 videos professionally recorded for training purposes by a high-profile video analyst. All measures were conducted by three independent observers.

Results: Sixteen frames were finally included. The mean carrying angle was 11.5° ± 4.7°. The intraclass correlation coefficient value was 0.703, showing good reliability of the measurement technique. The measured carrying angle was lower than what has been observed in historical cohorts using comparable measurement methodology, suggesting a possible instant varus accommodation mechanism before hitting the ball.

Conclusions: The observed decrease in the carrying angle is a consequence of an increase in elbow flexion position dictated by the transition from a closed to open, semi-open stances. As the elbow flexes during the preparation phase, it is less constrained by the olecranon and its fossa, increasing the strain on the medial collateral ligament and capsule structures. Moving towards full extension before the ball-racket contact, the elbow is dynamically stabilised by a contraction of the flexor muscles. These observations could provide a new explanation for medial elbow injuries among elite tennis players and drive specific rehabilitation protocols.

Abbreviations: aMCL, anterior medial collateral ligament; DIVA, dynamic instant varus accommodation; ICC, intraclass correlation coefficient; SD, standard deviation.

Paolo Arrigoni and Davide Cucchi contributed equally to this study.

Study Design: Descriptive epidemiology study.

Level of Evidence: Level IV.

KEYWORDS

elbow, tennis, trauma, varus

INTRODUCTION

Tennis is a biomechanically demanding sport, causing injuries on both the upper and lower extremities [1]. The quick, intense and repeated start-stop movements, during which players perform sudden changes of direction while running and striking a ball at high speeds induces high loading forces [2, 3]. Even if cranial, ocular and lower extremities' injuries are frequent, the ones affecting the upper body are rather sport specific [4, 5].

Elbow injuries are common occurrences in the elite tennis players and have been reported in the literature consistently as an area where repetitive loading impacts the medial and lateral structures [6]. A basic understanding of tennis' biomechanics and analysis of elbow's forces, loads and motions during different tennis strokes helps to improve the understanding of the pathophysiology of these injuries [7–10]. Medial elbow pain is one of the most frequent diagnoses in elite male professional tennis players and comprise 35% of all the injuries evaluated in the elbow. It is the most common elbow diagnosis in professional male tennis players. The ratio of medial to lateral elbow problems is estimated to be 2:1 according to ATP official records. One of the main changes over the last 10 years has been an increase in the number of players that adopted an open stance position, which implies a more frontal position to the net during the preparation phase of the forehand. With this stance change, the loading phase is transferred on the shoulder, which needs to be more externally rotated, and on the forearm, which becomes more hyper-supinated [11].

Prior studies have highlighted a diagnosis of posteromedial impingement as a cause of olecranon valgus maltracking and terminal stiffness [12, 13]. This maltracking should be evident at almost full extension. Assuming that before the stiffness phase there would be a maltracking phase with a clear valgus deviation of the elbow, we aimed at verifying it in forehands [14–16]. Furthermore, the unicity of this study population consists of studying elite tennis players, a sub-population that expresses a technique considered to be absolutely correct and expressing a performance level that cannot match with a persistent pathology.

The main hypothesis is that elite tennis players tend to overstress their elbow in valgus over the physiological degree in the frontal plane just before ball contact on forehand groundstrokes, thereby provoking medial elbow pain, maltracking and stiffness. To confirm or reject this hypothesis could improve understanding of medial elbow injuries in elite tennis players and drive specific rehabilitation protocols.

MATERIALS AND METHODS

The goal of this observational study was to use image analysis recordings to measure the carrying angle of elite male tennis players during the forehand stroke.

Image analysis is a widespread off-court method exploited to provide top tennis players with a method for fine-tuning the athletic gesture [17]. The method is well known among top athletes, since it allows analysis of the gesture once off-court.

All players provided their consent for the acquisition of video material, also authorising its processing. Since the video acquisition was carried out with the aim of enhancing athletic performance before the beginning of this investigation and the videos are in the public domain, there was no need for ethical committee authorisation to conduct this investigation.

The recording method consists of a variable number of cameras, located around the tennis court, capturing the athlete's adjustments on a timespan of a fraction of a second. The specific acquisition setting used for this study was established by a high-profile video analyst and consisted of four cameras located around the tennis court; two placed lateral, one anterior, and one posterior with respect to the player's position.

Each camera records the athletic gesture by taking 60 frames per second and can be used to generate a slow-motion video of 1–2 min duration. Frontal acquisitions were chosen for this study, as they are considered the most reproducible perspective to acquire frontal elbow images on the tennis court and measure the athlete's carrying angle.

Videos were considered eligible for inclusion if they depicted a top-level male tennis player, defined as one athlete being ranked in the top 25 positions in the ATP ranking at the time of the acquisition of the video, and if they included frontal views of the player performing a forehand groundstroke (Figure 1). The seasons of acquisition were restricted to the period between 2014 and 2016. Included videos were analysed and subsequently cut to obtain the best frontal frame just before the ball-racket contact, with the elbow as close as

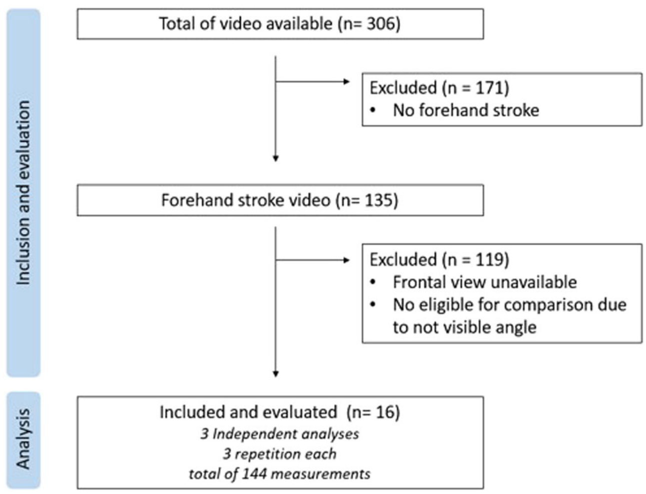

FIGURE 1 Study flowchart illustrating the flow of videos and measurements in the study.

FIGURE 2 Schematic illustration of the goniometric measurement of the carrying angle on a selected video frame.

possible to full extension. These frames were converted to black-white images to minimise possible colour- and contrast-related bias and the faces of the players were obscured.

The carrying angle was calculated adapting the measurement protocol proposed by Zampagni et al. [18] for digitised point acquisition in a reference system relevant to the arm and forearm on the previously described clinical goniometric referencing method described by Atkinson and Elftman [19]. This latter method references on the medial profile of the upper arm, the prominence of the medial epicondyle of the humerus and the medial surface of the forearm reaching the prominence of the head of the ulna [20–22] (Figure 2).

The frames selected for analysis were sorted in random order and three independent observers, each of whom working as an orthopaedic surgeon for elbow pathologies, measured the carrying angle with the aforementioned method. All measurements were conducted with one decimal degree of accuracy and repeated in triplicate, with a 1-week delay between the measurements and mixing the order of the frames selected for analysis between each measurement repetition to reduce recall bias.

Statistical analysis

Statistical analysis was performed using GraphPad Prism v 6.0 software (GraphPad Software Inc.) and Microsoft Excel (Microsoft Corporation). The Shapiro–Wilk normality test was used to evaluate the normal distribution of the sample. Continuous variables were expressed as the mean ± standard deviation (SD) or medians, and first and third quartiles [Q1–Q3], as appropriate. Interobserver agreement was calculated by using the intraclass correlation coefficient (ICC) on the measurements of the investigated parameters and interpreted according to the guidelines of Fleiss: values less than 0.4 indicate poor reliability, values between 0.4 and 0.75 indicate good reliability, and values greater than 0.75 indicate excellent reliability [23]. The differences for continuous variables between the study cohort and reference works were proved with an unpaired Student's *t*-test or Mann–Whitney test according to the characteristics of the data distribution. For all analyses, the significance level was set at a *p*-value lower than 0.05.

No power analysis was performed before study begin, since the strictly defined season frame (2014–2016) and the restriction to elite players automatically limited the possibility of expanding the sample acquisition. Considering previous similar publications, a sample size of 10–15 measurements was deemed as acceptable for this research purpose [24, 25].

RESULTS

Three hundred and six videos were assessed for eligibility and 16 were finally included. Figure 1 illustrates the flow of videos and measurements in the current study.

One hundred and forty-four measurements were obtained. The mean carrying angle was 11.5° ± 4.7° (Observer 1: 11.5° ± 4.9°; Observer 2: 9.9° ± 4.8°; Observer 3: 13.2° ± 5.0°) The ICC value was 0.703 (Observer 1: 0.849; Observer 2: 0.669; Observer 3:

0.744), showing good reliability of the measurement technique.

Comparing the study population to the historical cohorts using comparable measurement methodology presented by Atkinson and Elftman and by Paraskevas et al., a significant difference emerged between the expected means previously described and the measurements obtained in this study, showing a significantly greater valgus carrying angle in the subgroup of top male tennis players during forehand stroke (Aktinson and Elftman: subgroup of 105 adult males, carrying angle of 14.4°, $p = 0.0203$; Paraskevas et al.: subgroup of 168 athletic males, carrying angle of 13.89° right and 12.66° left, $p = 0.0493$ and n.s.) [19, 26].

DISCUSSION

The most important finding of the present study was that, just before ball contact on forehand groundstrokes, the carrying angle of top male tennis players is reduced with respect to the physiological one estimated to be approximately 15°. Our hypothesis was therefore refused.

As opposed to the expected overstress in valgus, a varus accommodation of the elbow just before the ball-racket contact was observed in the images analysed. This previously undescribed behaviour, probably accounting for pathologic changes in the medial elbow compartment over the long run, was termed dynamic instant varus accommodation (DIVA).

This varus accommodation could be related to a sudden contraction to the flexor pronator mass to reduce the valgus stress dominating the loading phase at the elbow. Such DIVA would be an essential compensatory mechanism to correctly engage the olecranon into the olecranon fossa, complete the stroke, and reach the forehand hitting position.

Players hitting forehands can use different type of stances, which refer to feet and hip placement during the stoke: closed, with feet and hips perpendicular to the net, open where they are parallel the net and semi-open stance that describes any foot positioning between the closed and open stances [11]. Trunk rotation, which is relevant in the loading phase, decreases from closed to open stances, with relevant implications for the shoulder and elbow joints [2]. In the last few years, the game has consistently accelerated with high-level tennis players giving priority to open stances to save time during defensive baseline forehands. This position presents a lack of rotation in shoulders and trunk. This would determine a reduction in racket speed, that is compensated by increased external rotation of the shoulder and increased speed of the shoulder movements to contribute to the net speed of the racket at the moment of impact [27, 28]. As a consequence of these changes, playing in open and semi-open stances places the elbow in a more flexed position during the loading phase, with an increased valgus stress, which puts under major tension the medial collateral ligament, particularly its anterior bundle (aMCL) [2] (Figure 3).

Previous studies have postulated a persistence of this valgus deviation also immediately before impact of the racket with the ball, with valgus maltracking of the olecranon leading in the long run to posteromedial impingement and terminal stiffness [12, 13]. However, as opposed to this expected overstress in valgus, a varus accommodation of the elbow just before the ball-racket contact was observed in this study, which suggest a further mechanism for medial elbow pathology development in top tennis players. This dynamic varus accommodation appears to alter the carrying angle significantly from the values measured in previous studies with similar methodology.

The carrying angle of the elbow refers to the obliquity between the upper arm and the supinated

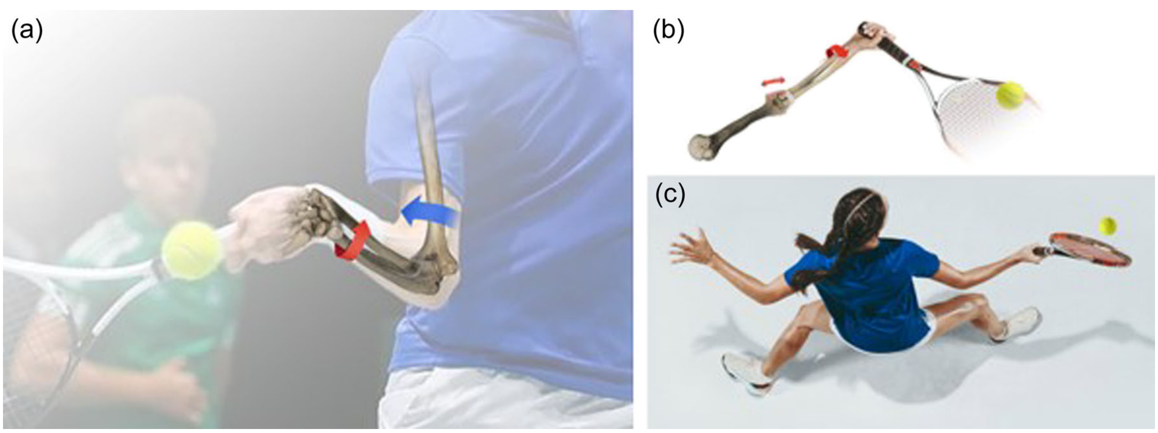

FIGURE 3 Graphic representation of the forces acting on the medial aspect of the elbow (a, b), playing in open and semi-open stances places (c): playing with the elbow in a more flexed position during the loading phase causes an increased valgus stress, which puts under tension the anterior bundle of the medial collateral ligament.

forearm when the elbow is held in extension [18, 21, 29–31]. Due to relevant differences in the measurement concepts, different mean values of the carrying angle have been reported from 6.7° to over 20° in adults, making the comparison of different studies difficult and restricted to those with similar methodology [21, 32]. For this reason, a statistical comparison was performed only with the mean values reported by Atkinson and Elftman and by Paraskevas et al., whose measurement method is comparable to that of the present study [19, 26]. Interestingly, a significant difference emerged between their previously described means and the measurements obtained in the currents study, showing a significantly greater valgus carrying angle in the subgroup of top male tennis players during the forehand stroke. Of particular interest is the comparison with the carrying angle of a subgroup of right elbows in athletic males published by Paraskevas et al., which appears markedly higher than that observed in the cohort evaluated in the current study (13.9° vs. 11.5°, $p < 0.05$) [26].

The carrying angle plays a relevant role in the fine-tuning of muscular lever arms in arm movements [21, 29, 33]. Abduction and adduction may also affect the carrying angle, with the medial and lateral ligamentous complexes providing a constraint against excessive varus or valgus deviations: Amis et al. estimated that the collateral ligaments allow approximately nine degrees range of movement, with their control being closer near the limits of flexion and extension [29].

The previously undescribed varus accommodation of the elbow just before the ball-racket contact observed in our series of top male tennis players (DIVA) could indeed be related to a weakening of this collateral ligament control mechanism near to full extension, over the long run possibly accounting for pathologic changes in the medial elbow compartment.

Near full extension a higher strain of the aMCL is expected for two reasons: first, in order to reach a more extreme and posterior wrist position to maximise racquet head velocity once ball contact is established; second, because by playing in open and semi-open stances with a more flexed elbow the bony contribution to stability is reduced, in favour of a greater role of the soft tissues to maintain a stable elbow (Figure 4). Herewith, the observed DIVA would be an adaptive mechanism to modern gameplay and the utilisation of semi-open and open stance positions, which shift the impact point with the ball anteriorly. Consequently, this alteration in ball impact point results in changes in wrist, forearm, elbow and shoulder positioning. As opposed to the shoulder, which stance-depending changes have been previously detailed [34], no previous dealt with elbow changes. A further intriguing consideration to drive future research would be to investigate whether this stance shift has led to a change in wrist kinematic and to a higher incidence of wrist injuries.

The muscles of the flexor pronator mass are expected to play a major role in these players to compensate for aMCL strain with possible elongation, since they act as secondary, soft tissue stabilisers.

Therefore, the observed DIVA could be related to a sudden contraction of the flexor pronator mass to reduce the valgus stress dominating the loading phase and overloading the aMCL. This would be an essential compensatory mechanism to correctly engage the olecranon into the olecranon fossa and complete the stroke and reach the hitting position, however possibly

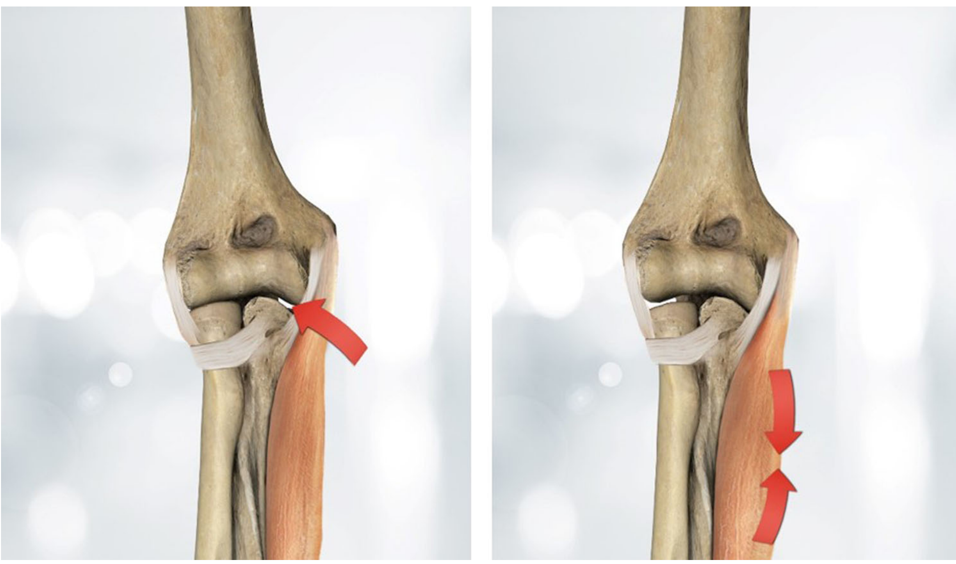

FIGURE 4 Graphic representation of the mechanism of muscular compensation following aMCL overload: the activation of the flexor-pronator muscles causes a dynamic instant varus accommodation when closing towards full extension before the ball-racket contact, permitting the olecranon to engage into the olecranon fossa.

accounting for pathologic changes in the medial elbow compartment over the long run.

This paper doesn't change the idea that at elbow extension, the olecranon may maltrack causing a posterior impingement. Still, it might be of interest to study in the future how long the elbow would potentially take to become stiff at the extreme degrees, as a consequence of the flexors' recruitment, mitigating a medially based elbow pain. Finally, a future study direction will be to test the medial patholaxity at rest of tennis players that should be augmented to 'research' an augmented valgus stress.

Regarding the possible therapeutical consequences of the findings described in this study, the observation of a DIVA associated with medial elbow pain could drive a specific rehabilitation protocol: considering the role of dynamic stabilisers, a rehabilitation strategy aimed at optimising the load/load capacity ratio of the muscle complex surrounding the elbow becomes imperative. This is particularly relevant given that the more the elbow moves into flexion, the more the musculotendinous elements experience heightened loads.

Limitations in this study are the relatively small sample size, which is dictated to the extremely strict inclusion criteria applied in order to enrol only a high-performance subpopulation that expresses a technique considered to be absolutely correct; this may limit the generalisability of the findings to the broader population of male tennis players, including recreational athletes. Second, the study only included male tennis players and did not include female tennis players. This may limit the generalisability of the findings to female tennis players. Sex-specific biological and biomechanical characteristics make women and men differently prone to certain injuries, not only among tennis players but also in other sportsmen and sportswomen [35, 36]. Many reasons have been postulated to explain the increased risk, including anatomical, biomechanical, neuromuscular and hormonal differences; focusing on the upper limb, an increased propensity towards generalised joint laxity and a different molecular composition of the tendon tissue could lead to a higher frequency of instability-related complaints and tendinopathies in female athletes; nevertheless, current literature evidence for elbow lesions is limited, inconclusive and presents controversial results [37, 38].

As a further limitation, the measurements were performed on bi-dimensional images, which can minimally bias measurements due to perspective distortion; the authors tried to avoid this by carrying out a meticulous selection of the 306 available videos and accepting only the 16 images deemed unbiased. The application of wearable sensors, which is now gaining popularity in orthopaedics and sports medicine, was not considered in the time frame 2014–2016 since potentially altering the athletic gesture; nevertheless, comparable accuracy of bi- and tridimensional measurement methods for the carrying angles was reported, supporting the use of a bidimensional method in this selected population [18, 39, 40]. For obvious reasons, radiological measurements of the carrying angle were also not possible. Moreover, the study only measured the carrying angle during the forehand stroke and did not measure the carrying angle during other tennis strokes, which may be important in understanding the overall risk of medial elbow injuries in elite male tennis players. Finally, due to the observational design of the study, the possibility to establish a causal relationship between the carrying angle and the incidence of medial elbow injuries in elite male tennis players is limited. Despite these limitations, the findings observed offer a novel understanding of medial elbow injuries among elite tennis players. The concept of DIVA, as proposed, could influence specific rehabilitation protocols in the future.

CONCLUSIONS

While hitting the ball during forehand, the carrying angle of top male tennis players is reduced with respect to the physiological one: this previously undescribed compensatory behaviour triggered by contraction of the flexor-pronator muscles was termed dynamic instant varus accommodation. This accommodation compensates for the increased strain on the medial collateral ligament by dynamically reducing the elbow when closing towards full extension before the ball-racket contact, permitting the olecranon to engage into the olecranon fossa and complete the forehand stroke reaching the hitting position.

AUTHOR CONTRIBUTIONS

PA: Conceived and designed the analysis; collected the data; contributed data or analysis tools; performed the analysis; wrote the paper. **DC:** Conceived and designed the analysis; contributed data or analysis tools; performed the analysis; wrote the paper. **GB:** Collected the data; performed the analysis; wrote the paper. **RR:** Collected the data; performed the analysis; wrote the paper. **CC:** Contributed data or analysis tools; wrote the paper. **TE:** Contributed data or analysis tools; wrote the paper. **PSR:** Conceived and designed the analysis; contributed data or analysis tools; wrote the paper.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

ETHICS STATEMENT

This material is the authors' own original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere. The paper reflects the authors' own research and analysis in a truthful and complete manner. The paper properly credits the meaningful contributions of co-authors and co-researchers. The results are appropriately placed in the context of prior and existing research. All sources used are properly disclosed. All authors have been personally and actively involved in substantial work leading to the paper, and take public responsibility for its content.

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REFERENCES

1. Abrams, G.D., Renstrom, P.A. & Safran, M.R. (2012) Epidemiology of musculoskeletal injury in the tennis player. *British Journal of Sports Medicine*, 46(7), 492–498.
2. Martin, C., Sorel, A., Touzard, P., Bideau, B., Gaborit, R., DeGroot, H. et al. (2020) Can the open stance forehand increase the risk of hip injuries in tennis players? *Orthopaedic Journal of Sports Medicine*, 8(12), 232596712096629. Available from: https://doi.org/10.1177/2325967120966297
3. Mohandhas, B.R., Makaram, N., Drew, T.S., Wang, W., Arnold, G.P. & Abboud, R.J. (2016) Racquet string tension directly affects force experienced at the elbow: implications for the development of lateral epicondylitis in tennis players. *Shoulder & Elbow*, 8(3), 184–191.
4. Musa, R.M., Hassan, I., Abdullah, M.R., Latiff Azmi, M.N., Abdul Majeed, A.P.P. & Abu Osman, N.A. (2022) A longitudinal analysis of injury characteristics among elite and amateur tennis players at different tournaments from electronic newspaper reports. *Frontiers in Public Health*, 10. 835119. Available from: https://doi.org/10.3389/fpubh.2022.835119
5. Patel, P.S., Uppuluri, A., Oydanich, M., Langer, P.D., Zarbin, M.A. & Bhagat, N. (2023) Epidemiology of United States tennis-related ocular injuries from 2000 to 2019. *International Ophthalmology*, 43(3), 997–1003.
6. Shannon, N., Cable, B., Wood, T., & Kelly, IV, J. (2020) Common and less well-known upper-limb injuries in elite tennis players. *Current Sports Medicine Reports*, 19(10), 414–421.
7. Chung, K.C. & Lark, M.E. (2017) Upper extremity injuries in tennis players: diagnosis, treatment, and management. *Hand Clinics*, 33(1), 175–186.
8. Elliott, B. (2006) Biomechanics and tennis. *British Journal of Sports Medicine*, 40(5), 392–396.
9. Eygendaal, D., Rahussen, F.T.G. & Diercks, R.L. (2007) Biomechanics of the elbow joint in tennis players and relation to pathology. *British Journal of Sports Medicine*, 41(11), 820–823.
10. Fu, M.C., Ellenbecker, T.S., Renstrom, P.A., Windler, G.S. & Dines, D.M. (2018) Epidemiology of injuries in tennis players. *Current Reviews in Musculoskeletal Medicine*, 11(1), 1–5. Available from: https://doi.org/10.1007/s12178-018-9452-9
11. Reid, M., Elliott, B. & Crespo, M. (2013) Mechanics and learning practices associated with the tennis forehand: a review. *Journal of Sports Science & Medicine*, 12(2), 225–231.
12. Bell, T.H., Ferreira, L.M., McDonald, C.P., Johnson, J.A. & King, G.J. (2010) Contribution of the olecranon to elbow stability: an in vitro biomechanical study. *The Journal of Bone and Joint Surgery-American Volume*, 92(4), 949–957.
13. Bowers, R.L., Lourie, G.M. & Griffith, T.B. (2022) Diagnosis and treatment of posteromedial elbow impingement in the throwing athlete. *Current Reviews in Musculoskeletal Medicine*, 15(6), 513–520.
14. Ellenbecker, T., Roetert, E.P., Petracek, K., Kovacs, M., Barajas, N. & Bailie, D. (2022) Bilateral comparison of anterior shoulder position in elite tennis players. *International Journal of Sports Physical Therapy*, 17(5), 863–869.
15. Redler, L.H. & Dines, J.S. (2015) Elbow trauma in the athlete. *Hand Clinics*, 31(4), 663–681.
16. Saini, S.S., Shah, S.S. & Curtis, A.S. (2020) Scapular dyskinesis and the kinetic chain: recognizing dysfunction and treating injury in the tennis athlete. *Current Reviews in Musculoskeletal Medicine*, 13(6), 748–756.
17. Myers, N.L., Kibler, W.B., Lamborn, L., Smith, B.J., English, T., Jacobs, C. et al. (2017) Reliability and validity of a biomechanically based analysis method for the tennis serve. *International Journal of Sports Physical Therapy*, 12(3), 437–449.
18. Zampagni, M.L., Casino, D., Martelli, S., Visani, A. & Marcacci, M. (2008) A protocol for clinical evaluation of the carrying angle of the elbow by anatomic landmarks. *Journal of Shoulder and Elbow Surgery*, 17(1), 106–112.
19. Atkinson, W.B. & Elftman, H. (1945) The carrying angle of the human arm as a secondary sex character. *The Anatomical Record*, 91, 49–52.
20. Patel, M.R. & Verma, S. (2020) Effect of varying carrying angle on grip strength in normal young individuals. *International Journal of Health Sciences Research*, 8(8), 159–166.
21. Van Roy, P., Baeyens, J.P., Fauvart, D., Lanssiers, R. & Clarijs, J.P. (2005) Arthro-kinematics of the elbow: study of the carrying angle. *Ergonomics*, 48(11–14), 1645–1656.
22. Zampagni, M.L., Casino, D., Zaffagnini, S., Visani, A. & Marcacci, M. (2008) Estimating the elbow carrying angle with an electrogoniometer: acquisition of data and reliability of measurements. *Orthopedics*, 31(4), 370. Available from: https://doi.org/10.3928/01477447-20080401-39
23. Fleiss, J.L. (1999) *The design and analysis of clinical experiments*. John Wiley & Sons Ltd, pp. 1–32.
24. Busuttil, N.A., Reid, M., Connolly, M., Dascombe, B.J. & Middleton, K.J. (2022) A kinematic analysis of the upper limb during the topspin double-handed backhand stroke in tennis. *Sports Biomechanics*, 21(9), 1046–1064.
25. Whiteside, D., Elliott, B.C., Lay, B. & Reid, M. (2015) Coordination and variability in the elite female tennis serve. *Journal of Sports Sciences*, 33(7), 675–686.
26. Paraskevas, G., Papadopoulos, A., Papaziogas, B., Spanidou, S., Argiriadou, H. & Gigis, J. (2004) Study of the carrying angle of the human elbow joint in full extension: a morphometric analysis. *Surgical and Radiologic Anatomy*, 26(1), 19–23.
27. Seeley, M.K., Funk, M.D., Denning, W.M., Hager, R.L. & Hopkins, J.T. (2011) Tennis forehand kinematics change as post-impact ball speed is altered. *Sports Biomechanics*, 10(4), 415–426.
28. Tooth, C., Croisier, J.-L., Schwartz, C., Tubez, F., Gofflot, A., Bornheim, S. et al. (2022) The influence of growth and development on shoulder rotators strength in young male and female elite tennis players. *The Journal of Sports Medicine and Physical Fitness*, 62(12), 1638–1645.

29. Amis, A.A., Dowson, D., Unsworth, A., Miller, J.H. & Wright, V. (1977) An examination of the elbow articulation with particular reference to variation of the carrying angle. *Engineering in Medicine*, 6(3), 76–80.
30. Beals, R.K. (1976) The normal carrying angle of the elbow. A radiographic study of 422 patients. *Clinical Orthopaedics and Related Research*, 119(119), 194–196.
31. Keats, T.E., Teeslink, R., Diamond, A.E. & Williams, J.H. (1966) Normal axial relationships of the major joints. *Radiology*, 87(5), 904–907.
32. Potter, H.P. (1895) The obliquity of the arm of the female in extension. the relation of the forearm with the upper arm in flexion. *Journal of Anatomy and Physiology*, 29(4), 488–491.
33. Yilmaz, E., Karakurt, L., Belhan, O., Bulut, M., Serin, E. & Avci, M. (2005) Variation of carrying angle with age, sex, and special reference to side. *Orthopedics*, 28(11), 1360–1363.
34. Kawamoto, Y., Iino, Y., Yoshioka, S. & Fukashiro, S. (2019) Directionally compensated mechanical work provided by the shoulder leads to similar racket velocities during open and square stance forehand groundstrokes in tennis. *European Journal of Sport Science*, 19(7), 902–912.
35. Frank, R.M., Romeo, A.A., Bush-Joseph, C.A. & Bach, B.R. (2017) Injuries to the female athlete in 2017: part II: upper and lower-extremity injuries. *JBJS Reviews*, 5(10), e5. Available from: https://doi.org/10.2106/JBJS.RVW.17.00031
36. Stanley, L.E., Kerr, Z.Y., Dompier, T.P. & Padua, D.A. (2016) Sex differences in the incidence of anterior cruciate ligament, medial collateral ligament, and meniscal injuries in collegiate and high school sports: 2009-2010 through 2013-2014. *The American Journal of Sports Medicine*, 44(6), 1565–1572.
37. Sayampanathan, A.A., Basha, M. & Mitra, A.K. (2020) Risk factors of lateral epicondylitis: a meta-analysis. *The Surgeon*, 18(2), 122–128.
38. Wessel, L.E., Eliasberg, C.D., Bowen, E. & Sutton, K.M. (2021) Shoulder and elbow pathology in the female athlete: sex-specific considerations. *Journal of Shoulder and Elbow Surgery*, 30(5), 977–985.
39. Abuwarda, K. & Akl, A.-R. (2023) Changes in electromyographic activity of the dominant arm muscles during forehand stroke phases in wheelchair tennis. *Sensors*, 23(20), 8623. Available from: https://doi.org/10.3390/s23208623
40. Pedro, B., João, F., Lara, J.P.R., Cabral, S., Carvalho, J. & Veloso, A.P. (2022) Evaluation of upper limb joint contribution to racket head speed in elite tennis players using IMU sensors: comparison between the cross-court and inside-out attacking forehand drive. *Sensors*, 22(3), 1283. Available from: https://doi.org/10.3390/s22031283

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