

Original Research

Knee extensor/flexor muscle torque and jump performance in male volleyball players: effect of experience and torque-angle-velocity relationships

Ajlan SAÇ^{1,*}¹Department of Coaching Education, Faculty of Sports Sciences, Trakya University, 22030 Edirne, Turkey***Correspondence:** ajlansac@trakya.edu.tr (Ajlan SAÇ)**Abstract**

Background and objective: There are many studies that have examined the differences in isokinetic strength performance differences in athletes; however, observing these angular velocity-dependent differences on surface maps is a very practical and useful application. The aim of this study was to determine the angular velocity-dependent isokinetic knee extensor/flexor muscle strength and jump performance and to compare the test results and 3D torque-angle-velocity surface maps of amateur and professional volleyball players.

Materials and methods: We included 25 well-trained male volleyball players (14 professionals and 11 amateurs) with a mean age of 21.8 ± 2.6 years (range 18–27 years) in this cross-sectional study. The dominant knee concentric muscle contractions were analyzed at 300, 120, and 60°/s angular velocities to determine peak torque (PT), total work (TW), mean power (MP), angle of peak torque (APT), and hamstring-to-quadriceps torque ratio (H:Q). Vertical jump performance was assessed using countermovement jump (CMJ) test. These data were processed using a MATLAB algorithm for constructing the 3D torque-angle-velocity surface maps.

Results and conclusions: Significant differences were identified for extensor–flexor PT between PRO and AT at 300 and 120°/s ($p < 0.05$). Moreover, there were significant differences between groups for MP and APT at 300 and 120°/s for TW at all velocities. CMJ test results were significantly different between the groups ($p < 0.05$). Amateur and professional male volleyball players showed different concentric knee strengths across isokinetic velocities and different eccentric strengths on CMJ test. 3D surface maps can play an important role in the comparative analysis of athletes with different sports backgrounds or in performance analyses when tracking individual development and provide a detailed and understandable perspective in revealing differences. It can also be of help in detection of possible deficits in muscle strength and load range before and after potential injuries.

Keywords

Isokinetic; Knee; Muscle strength; Volleyball; 3D surface mapping

1. Introduction

The isokinetic dynamometer is one of the most reliable methods for assessing muscle strength in athletes [1, 2]. The isokinetic dynamometer is also considered the gold stan-

dard for determining the angular velocity-dependent torque, work, and power and agonist–antagonist muscle strength ratio [3, 4]. Peak torque (PT) is a good criterion for assessing joint function and muscle strength. The PT angle indicates the angle at which the muscles of the joint reach the PT

and the torque when the maximal muscle contraction occurs. These data are useful in designing training prescriptions and rehabilitation programs for athletes [5, 6].

Athletes show different strength parameters based on age, training history, and musculoskeletal development [7]. In addition, they may also have a history of acute or chronic injuries characterized by increased and frequent training intensity during their sports career [8]. These injuries are known to be mainly caused by an imbalance in strength between muscle groups or between the dominant and non-dominant leg [9, 10]. Therefore, it is critical to determine any agonist–antagonist muscle imbalances to accurately observe the strength parameters and minimize the risk of injury [11–13].

Studies focusing on the balance of lower limb strength in volleyball players show that the hamstring-to-quadriceps ratio (H:Q) varies depending on training history and experience. Additionally, the total work (TW) output of knee flexors seems to be lower in inexperienced and young athletes [13–18]. Lower limb strength is extremely important for athletes. In addition, a detailed analysis of angular velocity-dependent strength is believed to play an important role in training planning.

In volleyball, one of the popular sports, vertical jump skill is critical in blocking, offensive, and defensive moments [19, 20]. Strong knee joint muscles are required in the take-off and landing phases of the jump, and high levels of torque and power are required in the concentric/eccentric contractions of these muscles [13].

Isokinetic dynamometer tests are used to assess the relationship between torque and angle. Isolated analyses of peak torque, mean power, or total work parameters do not provide insights into the torque–angular velocity relationship of muscle strength. Although this relationship represents the dynamic behavior of the muscle, it also allows for a comprehensive analysis of functional capacity by revealing the lengthening–contraction, and lengthening–velocity relationships [21]. The torque and angle relationship is affected by increasing speed in dynamic evaluations [22]. Therefore, a three-dimensional (3D) surface map allows for a visual examination of the torque–velocity relationship and a more comprehensive analysis of the torque output in dynamic evaluations than that of static evaluations [22, 23].

The purpose of this study was to determine the angular velocity-dependent knee isokinetic extensor/flexor muscle strength and vertical jump performance in amateur and professional volleyball players and to compare test results and investigate torque–angle–velocity relationships by plotting 3D surface maps. We hypothesized that (1) PRO players have higher isokinetic test results and lower H:Q ratio, (2) Depending on experience PRO players can generate more power and their vertical jump performances are also better. (3) Isokinetic strength evaluations are not only based on torque–angle relationship; therefore, the dynamic torque capabilities can be better represented using 3D maps that are plotted by including the velocity parameter while performing a dynamic assessment.

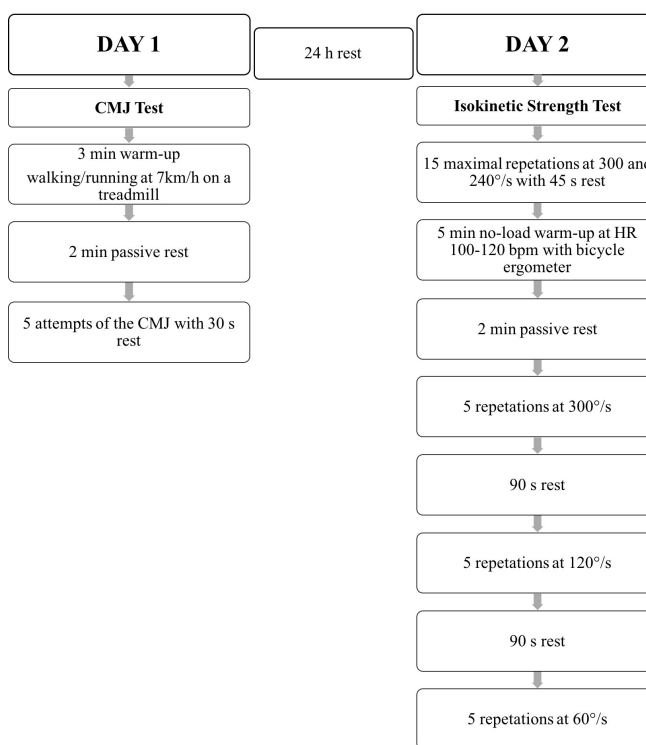


FIG. 1. Experimental design flowchart. CMJ, countermovement jump; km/h, kilometer per; s, second; HR, heart rate; bpm, beats per minute.

2. Methods

2.1 Study design

This was a cross-sectional laboratory study.

2.2 Participants

This study was conducted with the voluntary participation of 25 right-footed well-trained male volleyball players. Athletes who participated in the Turkish national leagues from different teams were divided into two groups: professionals (PRO) and amateurs (AT). The PRO group comprised the premier league athletes ($n = 14$) and the AT group comprised local league athletes ($n = 11$). Inclusion criteria were active volleyball athletes, of amateur or professional status, who had least 5 years' experience in training and participating in competitions, and performed training regularly for at least 3 d a week (frequency of training was 16 h/wk for PRO and 10 h/wk for AT). Those players who reported a major or moderate lower extremity injury or any injury to the knee or thigh and those taking any supplements were excluded (not meeting inclusion criteria: $n = 3$; refused to participate: $n = 1$).

2.2 Procedure

Testing sessions were conducted on 2 d with an interval of 24 h between them. On the first day, the purposes and methodological procedures of the study were presented to the athletes and an informed consent form was signed by the athletes. Body mass and height of the players were measured

TABLE 1. Anthropometric, countermovement jump test and hamstring-to-quadriceps ratio data.

| | PRO (n = 14) | | AT (n = 11) | | <i>p</i> |
|--------------------------|---------------------|------|---------------------|-------|----------|
| | Mean (min–max) | SD | Mean (min–max) | SD | |
| Age (year) | 22.2 (19–26) | 2.2 | 21.2 (18–27) | 3.1 | 0.349 |
| Height (cm) | 187.57 (181–193) | 4.18 | 183.18 (172–197) | 8.19 | 0.95 |
| Body mass (kg) | 82.07 (66–103) | 9.77 | 80.72 (63–110) | 12.48 | 0.765 |
| BMI (kg/m ²) | 23.35 (18.87–30.09) | 2.95 | 24.01 (20.68–30.47) | 2.92 | 0.586 |
| CMJ (cm) | 56.51 | 5.85 | 47.36 | 7.55 | 0.002* |
| H:Q (%) | 57.27 | 5.83 | 63.21 | 10.41 | 0.085 |

**p* < 0.05 level. PRO, professional; AT, amateur; SD, Standard Deviation; min, minimum; max, maximum; BMI, Body mass index; CMJ, Counter movement jump; H:Q, Hamstring to Quadriceps ratio.

with a digital device (Seca 769 scale, Seca GMBH, Hamburg, Germany). Later, the CMJ test was performed. On the second day, isokinetic strength test of the knee muscles was performed using an isokinetic dynamometer (Fig. 1).

2.3 Countermovement jump (CMJ) test

Participants performed a warm-up protocol composed of walking/running for 3 min at 7 km/h on a treadmill before the beginning the test. CMJ vertical jump test was performed to assess muscle strength performance of the lower limb and jump height [24]. For the CMJ performance, the participant started from the standing position with their hands on the hips. After an audible command, the participant performed hip and knee flexion (approximately 90°) in a quick movement, immediately followed by extension of these joints for the accomplishment of the highest jump as much as possible [25]. CMJ height was recorded with a high-speed camera (240 frames per second) (iPhone X, Apple Inc., San Francisco, CA, USA). After 5 CMJ tests with a rest interval of 30 s [26, 27], camera recordings were analyzed with motion tracking and analysis software (Kinovea 0.8.27) to determine the best CMJ height.

2.4 Isokinetic strength test

The isokinetic tests were conducted using the Humac NORM dynamometer and data were collected using Humac2009 v10 software (CSMI, Stoughton, MA, USA). Before the tests, the isokinetic strength test protocol was introduced and for adaptation, the participants were asked to do 15 maximal repetitions at 300 and 240°/s angular velocities with 45 s rest intervals. Before the test, a warm-up protocol was employed on a bicycle ergometer. Participants did a no-load warm-up exercise for 5 min, with their heart rate at 100–120 bpm. Muscle contractions were performed in concentric (con/con) mode using a knee joint apparatus. To allow participants to sit comfortably, the seat of the dynamometer was adjusted so that the hip joint angle was 85°. The knee joint range of motion was set at 90° (0° = full extension). All tests were performed with the dominant leg (the dominant leg was determined by the question “Which leg do you use to hit the ball?”) at angular velocities of 300, 120, and 60°/s. A 90 s rest break was given between the tests. For reliability purposes, a coefficient of variation less than 10%, for each

set, was considered acceptable [28]. Participants were asked to perform voluntary maximal concentric five extension–flexion movements at every angular velocity and a full range of motion (ROM) [29]. At the end of the test, PT, TW, MP, joint angle at peak torque (APT), and H:Q ratio parameters were recorded. H:Q ratio was assessed only at an angular velocity of 60°/s for a more precise result [30].

2.5 Three-dimensional surface maps

The 3D torque-angle-velocity surface maps were created with the MATLAB (r2014b, Math Works, Natick, MA, USA) algorithm using raw data obtained from the isokinetic strength test result. The “surf” mathematical function was used to create surface maps. All reps were used for the analysis and interpolated for all three angular velocities, in accordance with the duration and values of the average curves for each participant. To better describe surface maps, the entire ROM of extension–flexion motion was considered and polynomial regression curve was plotted for acceleration, constant speed (load range), and deceleration stages of the motion [15, 21]. 3D surface maps used Z-axis for the torque value, Y-axis for the angle value, and X-axis for the velocity value. The map used red color for high torque values and blue for low torque values.

2.6 Statistical analysis

The results were analyzed using IBM SPSS Statistics (Versions 22 for macOS; IBM, Armonk, NY, USA). The data were assessed for skewness and kurtosis with the skewness–kurtosis test. Data distribution was analyzed using the Shapiro–Wilk test, followed by Mann–Whitney test for cross-group comparisons. The effect size (\bar{d}) was determined for isokinetic test outputs at three different angular velocities. The level of significance for statistical analyses was set at *p* < 0.05.

3. Results

Participants’ descriptive statistics (14 professionals, 11 amateurs; average age: 21.8 ± 2.6 years range 18–27 years; height: 185.6 ± 6.5 cm; body mass: 81.4 ± 10.8 kg; body mass index: 23.6 ± 2.8 kg/m²), CMJ and H:Q values are presented in Table 1. There was no difference between groups except for

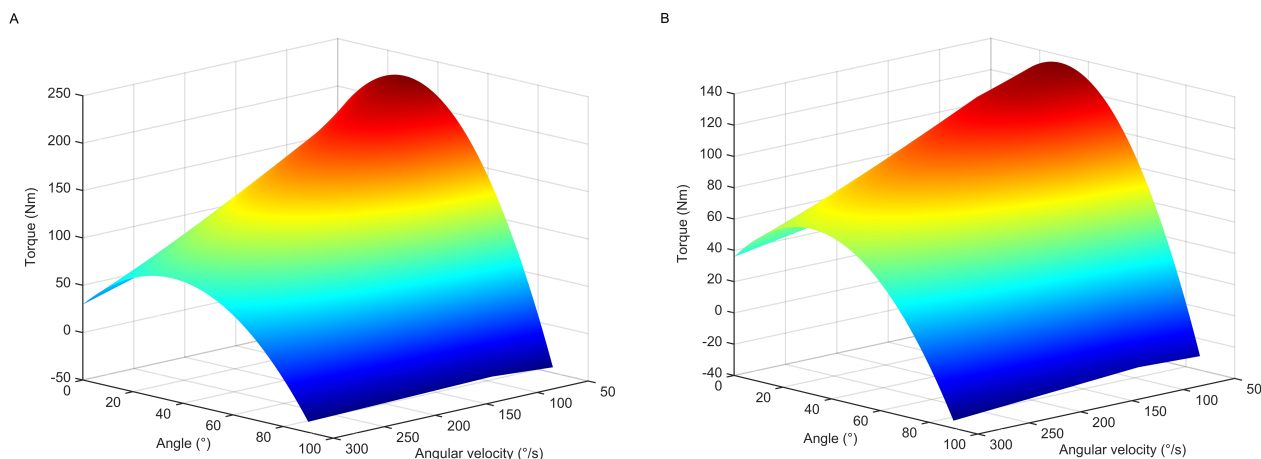


FIG. 2. 3D surface maps of extension torque-angle-velocity relationship. (A) Knee extension of the PRO players. (B) Knee extensions of the AT players. °/s: degrees per second; PRO, professional; AT, amateur; Nm, Newton-metre; x, angular velocity axis; y, angle axis; z, torque axis.

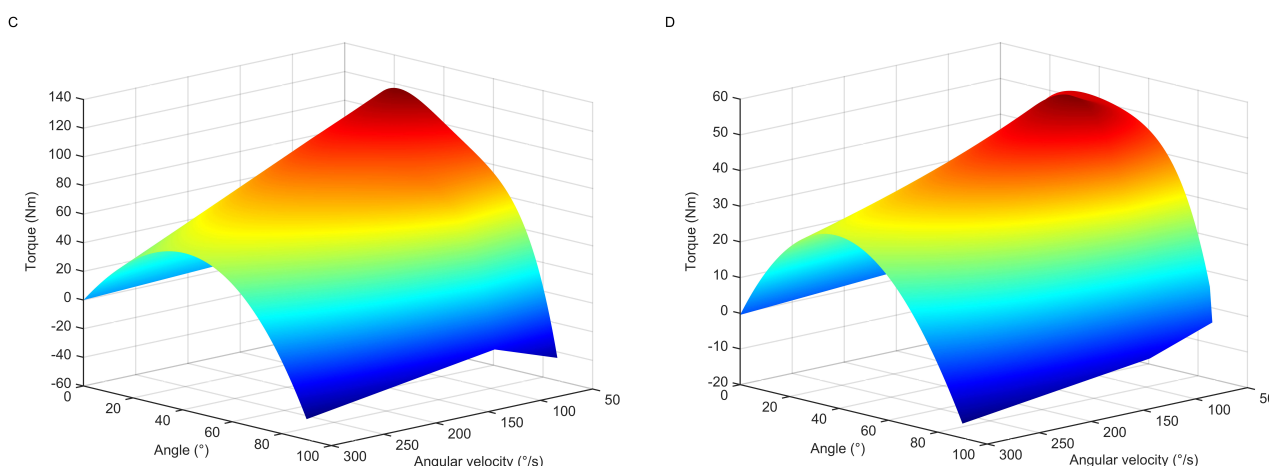


FIG. 3. 3D surface maps of flexion torque-angle-velocity relationship. (C) Knee flexion of the PRO players. (D) Knee flexion of the AT players. °/s, degrees per second; PRO, professional; AT, amateur; Nm, Newton-metre; x, angular velocity axis; y, angle axis; z, torque axis.

CMJ test output ($p < 0.05$).

A statistically significant difference was found in the extensor and flexor PT values in favor of PRO volleyball players at angular velocities of 300 and 120°/s ($p < 0.05$) (Tables 2,3). There was a statistically significant difference between groups in MP and APT parameters at 300 and 120°/s and in the TW parameter at all angular velocities (Tables 2,3). The H:Q ratio did not significantly differ for PRO and AT. A statistically significant difference was found between groups in CMJ test results as well ($p < 0.05$) (Table 1).

3D surface maps showed high torque values of extension and flexion in the red field for PRO and AT groups. Both groups achieved higher extensor torque values at low and medium angular velocities. High extensor torque values were detected in the first ROM angles following the start of a movement for both groups (Fig. 2). Flexor torque data showed less variation between angular velocities. High torque values were recorded in the terminal phase of the flexion movement for both groups (Fig. 3).

4. Discussion

The hypotheses were: (1) PRO players have higher isokinetic test results and lower H:Q ratio, (2) depending on experience PRO players can generate more power and their vertical jump performances are also better. (3) Isokinetic strength evaluations are not solely based on torque-angle relationship; therefore, the dynamic torque capabilities will be better represented by three-dimensional maps that can be plotted by including the velocity parameter while performing a dynamic assessment. The main finding of this study is more experienced athletes had higher peak torque, mean power, angle at peak torque in both extension and flexion movements at angular velocities of 300 and 120°/s (extensor 300°/s PRO = 62.42 ± 27.72 Nm, AT = 27.27 ± 16.41 Nm, ($p < 0.05$); 120°/s PRO = 159.57 ± 25.93 Nm, AT = 128.09 ± 25 Nm, ($p < 0.05$)), (flexor 300°/s PRO = 48.28 ± 18.54 Nm, AT = 17.36 ± 7.51 Nm, ($p < 0.001$); 120°/s PRO = $103.64 \pm$

TABLE 2. Isokinetic strength test results of extensor muscles.

| | 60°/s | | | | 120°/s | | | | 300°/s | | | |
|--------------------------|------------------|-----------------|----------|-----------|-----------------|-----------------|----------|-----------|-----------------|----------------|----------|-----------|
| | PRO | | <i>p</i> | \bar{d} | PRO | | <i>p</i> | \bar{d} | PRO | | <i>p</i> | \bar{d} |
| | Mean ± SD | Mean ± SD | | | Mean ± SD | Mean ± SD | | | Mean ± SD | Mean ± SD | | |
| Peak torque (Nm) | 191.42 ± 34.16 | 175.81 ± 34.21 | 0.269 | 0.46 | 159.57 ± 25.93 | 128.09 ± 25.1 | 0.006* | 1.23 | 62.42 ± 27.72 | 27.27 ± 16.41 | 0.001* | 1.49 |
| Total work (Nm) | 1017.14 ± 169.07 | 855.45 ± 173.06 | 0.028* | 0.95 | 863.92 ± 146.19 | 665.45 ± 158.90 | 0.004* | 1.31 | 274.64 ± 140.02 | 103.18 ± 70.64 | 0.001* | 1.48 |
| Mean power (W) | 125.42 ± 21.14 | 112.27 ± 16.66 | 0.105 | 0.68 | 195.35 ± 35.31 | 155.63 ± 29.58 | 0.007* | 1.21 | 117.28 ± 59.51 | 40.54 ± 30.38 | 0.001* | 1.56 |
| Angle at peak torque (°) | 68.71 ± 6.83 | 59.45 ± 8.22 | 0.005* | 1.24 | 61.14 ± 4.92 | 51.63 ± 6.98 | 0.001* | 1.61 | 62.21 ± 15.13 | 63.91 ± 16.05 | 0.789 | -0.11 |

* *p* < 0.05 level. °/s, degrees per second; PRO, professional; AT, amateur; SD, Standard Deviation; \bar{d} , effect size; Nm, Newton-metre; W, Watt; °, degree.

TABLE 3. Isokinetic strength test results of flexor muscles.

| | 60°/s | | | | 120°/s | | | | 300°/s | | | |
|--------------------------|-----------------|-----------------|----------|-----------|-----------------|-----------------|----------|-----------|----------------|---------------|----------|-----------|
| | PRO | | <i>p</i> | \bar{d} | PRO | | <i>p</i> | \bar{d} | PRO | | <i>p</i> | \bar{d} |
| | Mean ± SD | Mean ± SD | | | Mean ± SD | Mean ± SD | | | Mean ± SD | Mean ± SD | | |
| Peak torque (Nm) | 120.07 ± 22.84 | 108.72 ± 22.83 | 0.231 | 0.49 | 103.64 ± 17.83 | 80.36 ± 19.97 | 0.005* | 1.24 | 94.28 ± 18.54 | 17.36 ± 7.51 | <0.001* | 2.15 |
| Total work (Nm) | 751.42 ± 127.69 | 611.81 ± 157.45 | 0.221 | 0.99 | 635.71 ± 108.91 | 457.72 ± 143.84 | 0.002* | 1.42 | 209.28 ± 99.82 | 57.18 ± 41.06 | <0.001* | 1.89 |
| Mean power (W) | 92.21 ± 18.39 | 80.45 ± 16.57 | 0.111 | 0.67 | 143.78 ± 28.93 | 108.09 ± 28.85 | 0.005* | 1.21 | 88.14 ± 38.96 | 22.91 ± 14.22 | <0.001* | 2.12 |
| Angle at peak torque (°) | 32.51 ± 6.64 | 34.11 ± 8.33 | 0.611 | -0.21 | 38.85 ± 5.41 | 42.54 ± 12.94 | 0.343 | -0.39 | 45.64 ± 8.77 | 40.01 ± 18.12 | 0.316 | 0.41 |

* *p* < 0.05 level. °/s, degrees per second; PRO, professional; AT, amateur; SD, Standard Deviation; \bar{d} , effect size; Nm, Newton-metre; W, Watt; °, degree.

17.83 Nm, $AT = 80.36 \pm 19.97$ Nm, ($p < 0.05$)), and higher TW values at all angular velocities ($p < 0.05$). The same results were visually verified through examination of the participants' torque outputs by angular velocities on 3D surface maps plotted according to joint angles. In addition, low H:Q ratio and high CMJ height were found for PRO volleyball players (CMJ height PRO = 56.51 ± 5.85 cm, $AT = 47.36 \pm 7.55$ cm, ($p < 0.05$)). Based on these results, we could verify the hypotheses of this study.

Similar results have been obtained in other studies which were attributed to the difference in the training frequency and intensity of experienced high-level athletes and different levels of musculoskeletal development [7, 13, 15–18, 31].

The areas in which the high torque was shown in red in extension movements corresponded to a larger numerical value in PRO athletes, whereas the equivalents of these colors were smaller in AT athletes. By angular velocity, joint angle and high torque values at low and medium velocities (60 and 120°/s) pointed approximately to a range of 15°–60° for PRO and AT, whereas this range was between 25° and 45° at a high speed (300°/s). Likewise, examination of the flexion movements showed that high torque values varied less between angular velocities and the joint angle range was wider; further, the red-colored area was also more linear.

Regular and well-designed training programs, nutrition, and ideal recovery times can allow professional athletes to reduce injury rates. Furthermore, by attending regular training, the athletes can adapt to increased training load and to carry their biomotor abilities to a higher level thanks to a targeted performance increase. Professional athletes have trained for a longer duration than amateur athletes and the resulting increased strength parameters at different levels are known to enable professional athletes to produce higher torque. These differences support the findings of the study. Age and sports history are important criteria; however, as participants were not divided into age groups in this study, a comparative analysis based on age and maturity levels was not performed. Several studies have shown age-related changes in maximal and rapid strength that were reported in antagonist muscle groups [32–34]. This may also have affected the difference in performance between groups as an additional factor.

Jumping is a skill of specific importance in volleyball. Knee joint muscles are responsible for 49% of the TW produced during a vertical jump [35]. CMJ test results of PRO and AT athletes were found to cause cross-group differences in the study. This may be attributed to different torque output levels. Previous investigations have shown that reduced H:Q ratios in male volleyball players are related to better CMJ performances [10]. Prilutsky and Zatsiorasky [36] stated that reduced H:Q ratios may be related to the need of producing more mechanical work for a jump, which is due to the lower dissipation of the rotational energy between the knee muscles. In addition, it is known that isokinetic knee strength parameters are associated with vertical jumps rather than spike jumps and are related to quadriceps concentric values [10, 37].

According to the literature review, an ideal hamstring-to-quadriceps muscle strength balance and a healthy joint mean that this ratio is approximately 60% in healthy individuals [9, 18]. Similar results were obtained from our study; the H:Q ratio was very close to recommended reference values in both PRO and AT athletes. According to our findings, the dominant leg H:Q ratios of the PRO and AT groups were 57% and 63%, respectively. Ön *et al.* [16] compared volleyball players of the same age and with different years of training, found H:Q ratios for both limbs at 60 and 180°/s were ranged 56–63%. In different studies which compared team sports, an H:Q ratio of approximately 55% [18] and 56% [13] for volleyball players were found. Considering the results of several studies, they stated that H:Q ratio was lower for high-level athletes, and volleyball players have a risk in terms of possible knee injuries due to low H:Q ratios [13, 17, 18, 38]. Based on these results, reduction in the ability to decelerate knee extension (eccentric action of hamstring muscles) may result in an overload of the anterior cruciate ligament, thereby increasing joint instability and risk of injury [39, 40].

This study has certain limitations, particularly including the fact that it was conducted through the analysis of unilateral lower limb performance and in athletes with no history of injury. In the future, studies should be conducted in other sports branches through bilateral lower limb assessments to generate a more comprehensive analysis. In addition, study results including athletes with a history of injury may contribute to the rehabilitation process. In future studies, the research can be further detailed by examining the co-contraction of the extensor and flexor muscles at different angular velocities with electromyography.

We recommend future research to investigate the strength differences, 3D torque-angle-velocity using surface maps plotted using the data obtained from the isokinetic strength test to facilitate the investigation by a simultaneous display of test results at different angular velocities to contribute in designing strength training programs. The results of the study show that professional training and competition programs of professional volleyball players affect the the knee joint muscle strength. These results indicate the critical importance of designing customized strength training programs for athletes at different levels, even in the same sports and age group. These findings may help amateur athletes and coaches working with them to gain awareness about the isokinetic strength of the lower limb and pay attention to strength development by incorporating it into strength training programs. Conducting isokinetic tests for athletes before the competition season and repeating these tests after certain periods by considering macro/microcycles in annual training planning can be highly useful. In investigating athletes' performance parameters, 3D torque-angle-velocity surface maps plotted with the data obtained can simultaneously show test results at different angular velocities and can be useful in dynamic performance analyses, provide a comprehensive perspective, and facilitate the work of physicians examining the data in non-sports sciences settings who make frequent use of a dynamometer, e.g.,

in physical therapy, orthopedic rehabilitation, and athlete rehabilitation units.

5. Conclusions

According to the experience of the athletes, AT and PRO male volleyball player groups showed different values of concentric knee strength depending on the angular velocity. Also, their CMJ heights were significantly different, whereas H:Q ratios demonstrated no differences between groups.

3D surface maps can play an important role in the comparative analysis of athletes with different sports backgrounds or performance analyses when tracking individual development and would provide a detailed and understandable perspective in revealing differences. In addition, it can also help to observe the possible deficits in muscle strength and load range before and after potential injuries.

Author contributions

AS designed the data collection method, collected the data, analyzed the data, prepared tables and wrote the paper.

Ethics approval and consent to participate

This study was conducted according to the Declaration of Helsinki. Before the tests, all participants read and signed the informed consent form. The research protocol was approved by Trakya University Ethics Committee (TÜTF-BAEK 2019/473).

Acknowledgment

We thank all the subjects for participating in this study.

Funding

This research received no external funding.

Conflict of interest

The author declare no conflict of interest.

References

- [1] Verdijk LB, van Loon L, Meijer K, Savelberg HHCM. One-repetition maximum strength test represents a valid means to assess leg strength *in vivo* in humans. *Journal of Sports Sciences*. 2009; 27: 59–68.
- [2] Ly LP, Handelsman DJ. Muscle strength and ageing: methodological aspects of isokinetic dynamometry and androgen administration. *Clinical and Experimental Pharmacology & Physiology*. 2002; 29: 37–47.
- [3] Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. *PM & R*. 2011; 3: 472–479.
- [4] Taylor JD, Fletcher JP. Correlation between the 8-repetition maximum test and isokinetic dynamometry in the measurement of muscle strength of the knee extensors: a concurrent validity study. *Physiotherapy Theory and Practice*. 2013; 29: 335–341.
- [5] Harbo T, Brincks J, Andersen H. Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects. *European Journal of Applied Physiology*. 2012; 112: 267–275.
- [6] Kannus P. Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. *International Journal of Sports Medicine*. 1994; 15: S11–S18.
- [7] Gantois P, Pinto V, Castro KRd, João PV, Dantas P, Cabral BG. Skeletal age and explosive strength in young volleyball players. *Revista Brasileira de Cineantropometria & Desempenho Humano*. 2017; 19: 331–342.
- [8] Solgård L, Nielsen AB, Møller-Madsen B, Jacobsen BW, Yde J, Jensen J. Volleyball injuries presenting in casualty: a prospective study. *British Journal of Sports Medicine*. 1995; 29: 200–204.
- [9] Coombs R, Garbutt G. Developments in the use of the hamstring/quadriceps ratio for the assessment of muscle balance. *Journal of Sports Science & Medicine*. 2002; 1: 56–62.
- [10] Schons P, Da Rosa RG, Fischer G, Berriel GP, Fritsch CG, Nakamura FY, *et al.* The relationship between strength asymmetries and jumping performance in professional volleyball players. *Sports Biomechanics*. 2019; 18: 515–526.
- [11] Scatton-Silva R, Lessi GC, Lobato DFM, Serrão FV. Acceleration time, peak torque and time to peak torque in elite karate athletes. *Science & Sports*. 2012; 27: e31–e37.
- [12] Kim H, Lee J, Ahn S, Park M, Lee D. Influence of Anterior Cruciate Ligament Tear on Thigh Muscle Strength and Hamstring-to-Quadriceps Ratio: a Meta-Analysis. *PLoS ONE*. 2016; 11: e0146234.
- [13] Dervisević E, Hadžić V. Quadriceps and hamstrings strength in team sports: Basketball, football and volleyball. *Isokinetics and Exercise Science*. 2012; 20: 293–300.
- [14] Bittencourt NFN, Amaral GM, Anjos MTSd, D'Alessandro R, Aurélio Silva A, Fonseca ST. Isokinetic muscle evaluation of the knee joint in athletes of the Under-19 and Under-21 Male Brazilian National Volleyball Team. *Revista Brasileira de Medicina do Esporte*. 2005; 11: 331–336.
- [15] Pelegrinelli ARM, Dela Bela LF, Silva MF, Rodrigues LCR, Batista JP, Guenka LC, *et al.* Velocity-specific knee strength between professional and under-17 female volleyball players. *The South African Journal of Physiotherapy*. 2019; 75: 478.
- [16] Ön S, Diker G, Özkamçı H, Zileli R. Comparison of isokinetic leg peak torque, hamstring/quadriceps ratio and strength asymmetry of male volleyball players with similar age and different years of training. *Age*. 2021; 15: 859–863.
- [17] Hadzic V, Sattler T, Markovic G, Veselko M, Dervisevic E. The isokinetic strength profile of quadriceps and hamstrings in elite volleyball players. *Isokinetics and Exercise Science*. 2010; 18: 31–37.
- [18] Teixeira J, Carvalho P, Moreira C, Santos R. Isokinetic assessment of muscle imbalances and bilateral differences between knee extensors and flexors' strength in basketball, football, handball and volleyball athletes. *International Journal of Sports Science*. 2014; 4: 1–6.
- [19] Sattler T, Sekulic D, Hadzic V, Uljevic O, Dervisevic E. Vertical jumping tests in volleyball: reliability, validity, and playing-position specifics. *Journal of Strength and Conditioning Research*. 2012; 26: 1532–1538.
- [20] Martinez DB. Consideration for Power and Capacity in Volleyball Vertical Jump Performance. *Strength & Conditioning Journal*. 2017; 39: 36–48.
- [21] Mazuquin B, Bela LD, Pelegrinelli A, Dias J, Carregaro R, Selfe J, *et al.* Torque-angle-velocity relationships and muscle performance of professional and youth soccer players. *International Journal of Sports Medicine*. 2016; 37: 992–996.
- [22] Frey-Law LA, Laake A, Avin KG, Heitsman J, Marler T, Abdel-Malek K. Knee and elbow 3D strength surfaces: peak torque-angle-velocity relationships. *Journal of Applied Biomechanics*. 2012; 28: 726–737.
- [23] Schwartz FP, Bottaro M, Celes RS, Brown LE, Nascimento FADO. The influence of velocity overshoot movement artifact on isokinetic knee extension tests. *Journal of Sports Science & Medicine*. 2010; 9: 140–146.
- [24] Bridgeman LA, McGuigan MR, Gill ND, Dulson DK. Relationships between Concentric and Eccentric Strength and Countermovement

- Jump Performance in Resistance Trained Men. *Journal of Strength and Conditioning Research*. 2018; 32: 255–260.
- [25] Bosco C, Luhtanen P, Komi PV. A simple method for measurement of mechanical power in jumping. *European Journal of Applied Physiology and Occupational Physiology*. 1983; 50: 273–282.
- [26] Harrison B, Firth W, Rogers S, Tipple J, Marsden J, Freeman JA, *et al*. The relationship between isokinetic performance of hip and knee and jump performance in university rugby players. *Isokinetics and Exercise Science*. 2013; 21: 175–180.
- [27] Wilhelm EN, Radaelli R, da Silva BGC, Botton CE, Barbosa R, Bottaro M, *et al*. Single-joint isometric rate of torque development is not related to counter- movement jump performance in soccer players. *Isokinetics and Exercise Science*. 2013; 21: 181–186.
- [28] Malina RM, Cumming SP, Kontos AP, Eisenmann JC, Ribeiro B, Aroso J. Maturity-associated variation in sport-specific skills of youth soccer players aged 13–15 years. *Journal of Sports Sciences*. 2005; 23: 515–522.
- [29] Brown LE, Weir JP. ASEP Procedures Recommendation I: Accurate Assessment of Muscular Strength and Power. *Journal of Exercise Physiology*. 2001; 4: 1–21.
- [30] Lehnert M, Xaverová Z, De Ste Croix M. Changes in muscle strength in u19 soccer players during an annual training cycle. *Journal of Human Kinetics*. 2014; 42: 175–185.
- [31] Akarçesme C, Aytar SH. The comparison of lower extremity isokinetic strength in volleyball players according to the leagues. *World Journal of Education*. 2018; 8: 111–117.
- [32] Palmer TB, Followay BN, Thompson BJ. Age-related effects on maximal and rapid hamstrings/quadriceps strength capacities and vertical jump power in young and older females. *Aging Clinical and Experimental Research*. 2017; 29: 1231–1239.
- [33] Runnels ED, Bemben DA, Anderson MA, Bemben MG. Influence of age on isometric, isotonic, and isokinetic force production characteristics in men. *Journal of Geriatric Physical Therapy*. 2005; 28: 74–84.
- [34] Thompson BJ, Ryan ED, Sobolewski EJ, Conchola EC, Cramer JT. Age related differences in maximal and rapid torque characteristics of the leg extensors and flexors in young, middle-aged and old men. *Experimental Gerontology*. 2013; 48: 277–282.
- [35] Hubley CL, Wells RP. A work-energy approach to determine individual joint contributions to vertical jump performance. *European Journal of Applied Physiology and Occupational Physiology*. 1983; 50: 247–254.
- [36] Prilutsky BI, Zatsiorsky VM. Tendon action of two-joint muscles: transfer of mechanical energy between joints during jumping, landing, and running. *Journal of Biomechanics*. 1994; 27: 25–34.
- [37] Sattler T, Sekulic D, Esco MR, Mahmutovic I, Hadzic V. Analysis of the association between isokinetic knee strength with offensive and defensive jumping capacity in high-level female volleyball athletes. *Journal of Science and Medicine in Sport*. 2015; 18: 613–618.
- [38] Magalhães J, Oliveira J, Ascensão A, Soares J. Concentric quadriceps and hamstrings isokinetic strength in volleyball and soccer players. *The Journal of Sports Medicine and Physical Fitness*. 2004; 44: 119–125.
- [39] Kabacinski J, Murawa M, Mackala K, Dworak LB. Knee strength ratios in competitive female athletes. *PLoS ONE*. 2018; 13: e0191077.
- [40] Wilk KE, Romaniello WT, Soscia SM, Arrigo CA, Andrews JR. The Relationship between Subjective Knee Scores, Isokinetic Testing, and Functional Testing in the ACL-Reconstructed Knee. *Journal of Orthopaedic & Sports Physical Therapy*. 1994; 20: 60–73.