ORİJİNAL ARAŞTIRMA ORIGINAL RESEARCH

Relationships Among Vertical Jumping Performance, EMG Activation, and Knee Extensor and Flexor Muscle Strength in Turkish Elite Male Volleyball Players

Türk Elit Erkek Voleybolcularda Diz Ekstensör ve Fleksör Kas Kuvveti, EMG Aktivasyonu ve Dikey Sıçrama Performansı Arasındaki İlişkiler

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ABSTRACT Objective: The aim of this study was to determine the relationship among maximum isokinetic concentric knee torque, muscle activity (EMG) and vertical jumping height of Turkish elite male volleyball players. **Material and Methods:** Twelve elite male volleyball players were included voluntary in this study. EMG activity was recorded on the vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF) and biceps femoris (BF) muscles of volleyball players during five maximal isokinetic concentric-concentric contractions at 60°/s, 180°/s and 240°/s. Peak anaerobic power output was calculated using vertical jumping heights. A repeated measures analysis of variance (ANOVA) was used to compare torque values in different angular velocities. Pearson's correlation coefficient was used to evaluate the relationship between torque and muscle activation values. The statistical significance level was set at p<0.05. **Results:** The results of this study show that Hamstring/Quadriceps (H:Q) ratios are greatest at an angular velocity of 240°/s. Differences in EMG activity during isokinetic testing were observed between the knee extensor (VL, VM) and flexor muscles (BF) (p<0.05). Repeated maximal isokinetic concentric contractions caused to increase the EMG activity of the knee and flexor muscles (p<0.05). In this study, it is demonstrated that volleyball players produced significantly higher counter movement jumping (CMJ) heights than squat jumping (SJ) heights (10%) (p=0.028). The maximum power of a CMJ was higher than that of an SJ (p=0.000), concentric work (p=0.001) and peak anaerobic power (p=0.020). Additionally, negative correlation was observed between VM, RF and BF muscle activation and isokinetic concentric-concentric torque values. **Conclusion:** It was thus concluded that the muscle activity of the knee extensor and flexor muscles changes with change in isokinetic torque at different angular velocity and repetition.

Key Words: Muscle activation; torque; isokinetic force

ÖZET Amaç: Çalışmanın amacı Türk elit erkek voleybolcuların diz ekstansör ve fleksör kaslarının maksimum konsantrik tork, dikey sıçrama ve kassal aktivasyon (EMG) değerleri arasındaki ilişkileri belirlemektir. **Gereç ve Yöntemler:** On iki elit erkek voleybolcu gönüllü olarak çalışmaya dahil edilmiştir. Voleybolcuların vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF) ve biceps femoris (BF) kaslarının kassal aktiviteleri (EMG), 60°/s, 180°/s and 240°/s açısal hızlarda, 5 maksimal izokinetik konsantrik-konsantrik kasılma sırasında kayıt edilmiştir. Zirve anaerobik güç çıktısı, squat sıçrama (SS) ve aktif sıçrama (AS) verileri hesaplanarak oluşturulmuştur. Farklı açısal hızlarda elde edilen tork değerleri tekrarlayan ölçümlerde varyans analizi (ANOVA) ile karşılaştırılmıştır. Tork ve kassal aktivasyon değerleri arasındaki korelasyonlar Pearson korelasyon katsayısı göz önünde bulundurularak analiz edilmiştir. Bütün istatistiksel testlerin anlamlılık düzeyi p<0,05 olarak alınmıştır. **Bulgular:** Çalışmanın bulguları 240°/sn açısal hızda en büyük Hamstring/Quadriceps (H:Q) oranına ulaşıldığını göstermektedir. İzokinetik test sırasında diz ekstansör (VL, VM) ve fleksör kasların (BF) EMG aktivitelerinde farklılıklar gözlenmiştir (p<0,05). Tekrarlı maksimal konsantrik izokinetik kasılmalar, diz ekstensör ve fleksör kaslarının EMG aktivitesinde artışa neden olmuştur (p<0,05). Voleybolcuların sıçrama yükseklikleri karşılaştırıldığında voleybolcular önemli derecede daha yüksek AS (%10) ortaya koymuşlardır (p=0,028). Maksimum AS güç çıktısı (p=0,000), konsantrik iş (p=0,001) ve zirve anaerobik güç (p=0,020) değerleri SS'dan daha yüksektir (p<0,05). Bu bulgulara ek olarak, VM, RF ve BF kassal aktivasyon değerleri ile izokinetik konsantrik-konsantrik tork değerleri arasında negatif korelasyon gözlenmiştir. **Sonuç:** Sonuç olarak farklı açısal hız ve tekrarlarda diz ekstensör ve fleksör kaslarındaki EMG aktivitesi değişirken, izokinetik tork yanıtlarında da değişim gözlenmiştir.

Anahtar Kelimeler: Kas aktivasyonu; tork; izokinetik kuvvet

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Success in volleyball depends primarily on a player's strength, speed, and endurance, together with his body's peak mechanical power output. Explosive muscle strength is an important performance variable, as are motor properties such as jumping and sprinting.[1-4] Muscular strength also helps volleyball players avoid overload injuries. The bodily velocities achieved during volleyball games can require great muscular and neural activity. Training programs used by trainers and researchers can be isokinetic; applied as an open kinetic chain (OKC) or functional, applied as sports-specific movements in a closed kinetic chain (CKC). Testing the isokinetic and functional muscle strength of volleyball players is an important component of performance evaluation. A commonly tested motor task is the vertical jump, which is related to leg extensor muscle strength.[1-3,5] The vertical jump is the test most frequently used by trainers and researchers to identify lower body muscle strength.[6] The ability to jump vertically is one of the determining variables of volleyball performance.[7] Successful vertical jumps require coordination between muscle strength and net moment around the participating joints.[8] The squat jumping (SJ) and counter movement jumping (CMJ) are commonly used to measure lower extremity muscle strength and performance. The SJ starts with the knee flexed to nearly 90° and terminates with a concentric (CON) contraction of the knee and hip to push the body upward.[9] The CMJ starts at a standing position and requires the rapid flexion and eccentric contraction (lengthening) of the hip and knee extensors, increasing the muscles' length and movement in conjunction with a concentric, shortening contraction of the hip and knee extensors.[9] The CMJ involves an elastic muscle force, in contrast to the explosive strength of the muscles of the lower extremities.[9] A strength shortening cycle (SSC) requires strength and performance development compared with a purely concentric movement.[8,10] Therefore, trainers and athletes commonly use SSC to develop performance.[11] Enhancing rapid movements such as lower extremity vertical jumps requires (a) increased explosive muscle power, (b) maximized voluntary contraction and (c) increased elastic power through repeated jumping.[12] To maintain this power, neuromuscular fatigue, also termed "decreased muscle maximum power production capacity", should be delayed. Other indices of neuromuscular fatigue include the capacity of motor units to sustain muscle power and force, and failure to complete a movement.[13,14] Fatigue can be identified through electromyography (EMG=, in which it is represented as an increased signal amplitude and decreased spectral frequencies.[15] Muscle fatigue can also be quantified as a decrease in power or maximal force measured immediately after a fatiguing contraction.[16,17]

Muscle activation and isokinetic torque levels are often measured simultaneously, and this study provides important baseline information on neuromuscular activity around the knee. Rehabilitation programs have focused on restoring knee muscle function, and knee joint injuries can be prevented by the early identification of muscle imbalances.[18,19] Studies of neuromuscular fatigue have focused on the maximal voluntary power-production capacity of muscle groups, on maximal isometric/isokinetic strength measures, on vertical jumping heights and on the capacity of the leg extensors to produce explosive power. However, no studies have correlated these parameters in elite volleyball players.

The aim of this study was to determine the relationship among maximum isokinetic CON knee torque, EMG activity and vertical jumping height of Turkish elite male volleyball players. Our main hypotheses were the following: (a) increasing the angular velocity during maximal CON contraction would decrease the torque response of the knee extensor and flexors; (b) the torque production capacity of the leg extensors would be significantly higher than that of the leg flexors at all angular velocities; (c) the EMG activity of the leg flexors would be significantly lower than that of the leg extensors at all angular velocities; and (d) that increasing the number of maximal CON contractions would increase the muscle activity of the knee extensor and flexors.

MATERIAL AND METHODS

EXPERIMENTAL APPROACH

The knee extensor and flexor muscle torques, EMG activity and different vertical jumping performance characteristics of male volleyball players were measured in the Performance Laboratory at Anadolu University over two days, allowing time for pre-test familiarization. On the first visit, anthropometric measurements were completed and the subjects became familiar with the CMJ and SJ. On the second visit, data were collected as follows:

Participants performed warm-up exercises consisting of five minutes of pedaling on a cycle ergometer without resistance, two sets of 10 consecutive hops and five to six submaximal CMJ and SJ.

EMG sensors were applied and participants performed maximum voluntary isometric contractions (MVICs) of the RF, VL, VM, and long head of the BF muscles before exercise testing. EMG activity was recorded during the isokinetic test.

The orders of the angular velocities tested during the isokinetic test were randomized to minimize effect of fatigue on the results. The subjects were informed about the strength testing procedures and vertical jump tests 24-48 hours before data collection.

SUBJECTS

The study included 12 male Turkish volleyball players from the Faculty of Sport Science. The physical characteristics of these elite male volleyball players, who had participated in regional and university competitions, are shown in Table 1. All were healthy and uninjured at the time of testing, with no prior history of upper or lower limb injuries. All subjects were informed of the possible risks of the study and all provided informed written consent for their participation in the experiment. The experimental design conformed to the Declaration of Helsinki and was approved by the local ethics committee of Osmangazi University.

EMG RECORDING AND SIGNAL PROCESSING

Each participant's skin was cleaned with an alcohol wipe, and four wireless sensors (Delsys Trigno, Boston, MA) were placed on the subject's right leg at the following locations: RF at 50% of the way across the line from the anterior spina iliaca superior to the superior part of the patella: VL 2/3 of the way across the line from the anterior spina iliaca superior to the lateral side of the patella; VM 80% of the way across the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament; and BF midway across the line between the ischial tuberosity and the lateral epicondyle of the tibia (SENIAM). Sensors were tested prior to data collection to confirm their locations and to eliminate cross talk, after which they were secured with tape and wraps.

After sensor placement, the MVICs of the muscles were recorded with the subjects fastened to the Cybex isokinetic dynamometer (Humac Norm Testing and Rehabilitation System, USA). For each of the MVIC trials, the maximum value obtained was recorded. All EMG signals were normalized to the maximum EMG signals recorded during MVICs and are presented as MVIC%. The MVIC tests of the RF, VL and VM were based on knee extensions in a seated position with the knee at 65° (0° corresponds to full extension), whereas the MVIC tests of the hamstrings (long head of the BF) were assessed in a prone position with the knee at 30°.[20] The subjects performed one trial to understand the task, and then five repetitions of five seconds each. To achieve maximum effort, the subjects received standardized verbal encouragements during the test. A two min rest was given between contractions. EMG data processing was performed in Matlab (Math Works R2012a). The data were fully wave rectified, normalized and integrated. A 6th order, 20 Hz high-pass Butterworth filter was applied to remove unwanted noise and possible movement artifacts in the low-frequency regions of EMG signals. The pass band of the EMG ampli-

TABLE 1: Physical characteristics of the elite male volleyball players.

n	Age (year)	Height (cm)	Weight (kg)	Body Mass Index (BMI) (kg/m^2)	Sports Experience (years)	Total Sport Hours /Week
12	20.1±1.9	178±4.9	72.4±6.7	22.9±1.5	9.2±3.4	12 hours: 4 days*3 h per week

fier, the sampling rate, the window size of the moving root-mean square (RMS) filter and common mode rejection ratio (CMRR) were 10-450 Hz, 1000 Hz, 100 ms and 95 dB, respectively. The peak values of the MVIC normalized and rms filtered EMGs were calculated for each velocity tested (60°/s, 180°/s, and 240°/s). The maximum values of the first 5 s of the RMS filtered MVIC-EMGs were used in the EMG normalizations.

ISOKINETIC KNEE TORQUE MEASUREMENTS AND ANALYSİS

Flexor and extensor knee torque measurements of the subjects' dominant legs were measured in an isokinetic dynamometer (Cybex Norm Testing and Rehabilitation System, USA). Each subject sat fastened by a belt to the isokinetic dynamometer chair (hip angle: 90°) to prevent body movement. The femoral region of the leg was attached to the chair with tape. The region of the knee joint coinciding with the rotational axis was adjusted to the same alignment with the input shaft, and the starting point was determined while the knee was anatomically at 0°. The range of motion of the knee joint was set at 90°. The lower leg was fastened to the lever of the dynamometer. The test position was set as recommended by the manufacturer. A gravity correction was applied to the torque measurement to compensate for limb weight.[21] The subject was instructed to grab the stabilization handles during the test, to fully extend the leg and then to flex it as hard and quickly as possible (one maximal extension followed immediately by a reciprocal maximal flexion). Each subject was given three familiarization trials followed by 20 s of rest. Isokinetic concentric torque was assessed at three angular velocities: 60°/s, 180°/s and 240°/s. The order of the velocities was randomized through a counter-balanced design. Five repetitions were then performed at each velocity, and during these repetitions, the torque and EMG activity of the knee extensor and flexor muscles were synchronously recorded. A one min rest was provided before the next angular velocity was measured. Knee extensor and flexor torque values were normalized to the subject's body weight. To calculate the H:Q ratio, the value of the maximum peak torque of the hamstring muscles was divided by that of the quadriceps muscles for the 60°/s, 180°/s and 240°/s angular velocities. Results for the strength of the dominant leg were used for statistical analyses. The dominant leg was defined as the preferred leg used for jumping.

JUMP TEST AND POWER ASSESSMENT

A wireless 3D inertial measurement unit (IMU) (Sensorize, Rome, Italy) was secured to the trunk at the L5 level by an elastic belt. The IMU contains a 3D accelerometer (full range to +6 g) and a 3D gyroscope (+5,008 at full range), providing 3D linear acceleration and 3D angular velocity with respect to a local embedded reference sensor that coincided with the geometrical axes of the IMU. Through a Bluetooth connection, the IMU data were sent at 100 Hz to a laptop computer and low-pass filtered using a fourth-order Butterworth filter at 20 and 15 Hz for acceleration and angular velocities, respectively.

Peak anaerobic power output was calculated by the equations below as shown in Table 2.

The counter movement jump tests were performed in the following order: (a) upright standing posture, (b) making a preliminary downward movement through knee and hip flexion [self-selected, called the preferred position (CMJ_{PREF})], (c) followed by an immediate, forceful extension of the knee and hip joints propelling the subject vertically off the ground[10] and (d) prior to take-off, extending the ankles to their maximum range (full plantar flexion) to ensure proper mechanics.[22] The squat jump test started from a stationary semi-squatting position with 90° of knee joint flexion and involved only knee extension.[23] Six jumps (separated by a three min rest) were used to record jumping height. To minimize the effect of arm swing on jump performance, the participants were asked to keep their hands on their hips.[24] Peak anaerobic power output was calculated by the equations. Flying times were determined using a bosco mat (Newtest 1000) and jumping heights were calculated using Formula 1. After calculating the jumping height, Formula 2 was used to evaluate the peak anaerobic power (PAP) (Table 2).[25]

TABLE 2: Vertical jump formulas.

Formula 1.	h=g.t2/8 = PAP(watt)
Formula 2.	Peak Power (W) = 60.7 x (jumping height [cm]) + 45.3 x (body mass [kg]) -2055

Formula 1: h= jumping height (cm); g= 9.81 m•s−2; t=time (sec).

STATISTICAL ANALYSIS

Analysis of Data

SPSS Version 21.0 (SPSS Inc., Chicago, IL) was used for all statistical analyses. Data were expressed as the mean ± standard deviation (X±SD). All the EMG and torque measurements were determined to be normally distributed using the Shapiro-Wilk test. Torque measurements were statistically analyzed (ANOVA) to test for angular velocity (60°/s, 180°/s, 240°/s) effects. Pearson's correlation coefficient (r) was used to assess the relationships between the torque measurements [60°/s torque × EMG; 180°/s torque × EMG; 240°/s torque × EMG; 60°/s torque × vertical jump heights (SJ and CMJ); 180°/s torque × vertical jump heights (SJ and CMJ); 240°/s torque × vertical jump heights (SJ and CMJ); and PAP × vertical jump heights (SJ and CMJ)]. Differences between the heights of the CMJ and SJ were assessed using the independent sample t-test. For all statistical tests, the significance level was set at $p<0.05$.

RESULTS

Peak torque (Nm) results and H:Q ratios (%) at different angular velocities (60º/s, 180º/s and 240º/s) for each subject are presented in Table 3 as the means ± standard deviations. The strength of concentric knee extension exceeded that of concentric knee flexion at all angular speeds (60º/s, 180º/s and 240º/s) ($p<0.001$) (Table 3). During maximal isokinetic CON contraction, the angular velocity increased as the maximal torque values decreased. H:Q ratios were greatest at an angular velocity of 240ºs/ (0.72±0.18). No differences were found among the H:Q ratios ($p>0.05$).

Peak torques and EMG activity curves as a percentage of MVIC for the knee extensor (VM, VL and RF) and flexor muscle groups (BF) at each isokinetic angular velocity tested (60º/s, 180º/s and 240º/s) over five repetitions are shown in Figure 1A, B, respectively.

At all angular velocities (60º/s, 180º/s and 240º/s) measured by the isokinetic dynamometer, the knee flexor muscles (BF) exhibited significantly higher ($p<0.05$) EMG activity than the knee extensor muscles (VL and VM). Nevertheless, the muscular activation of the RF and BF muscles did not differ significantly ($p>0.05$). During repeated maximal isokinetic CON contractions, the EMG activities of the knee extensor and flexor muscles increased. In response to 60°/s angular velocity, the VM muscle activity was 25% that of the MVIC and the knee joint torque was 287 Nm. Additionally, muscle activation and VM torque are negatively correlated during the first maximum isokinetic CON contraction at an angular velocity of 60º/and during the fifth maximum isokinetic CON contraction at an angular velocity of 240º/s (first repetition: r= -0.750; p=0.003; fifth repetition: r= -0.615; p=0.044).

TABLE 3: Hamstring and quadriceps peak torques (N.m) and H:Q ratios (%) at angular velocities 60º/s, 180º/s and 240º/s in the dominant knee.

Velocity (ºs-1)		Peak Torque for the Dominant Leg (N.m)	p	H:Q ratios (%)	p
60	H	193.4±11.8	0.000	0.65±0.15	>.05
	Q	304.6±17.4			
180	H	141.5±8.0	0.000	0.69±0.14	>.05
	Q	208.3±11.1			
240	H	123.8± 8.3	0.001	0.72±0.18	>.05
	Q	177.6±11.9			

H: Hamstring Muscles; Q: Quadriceps Muscles.

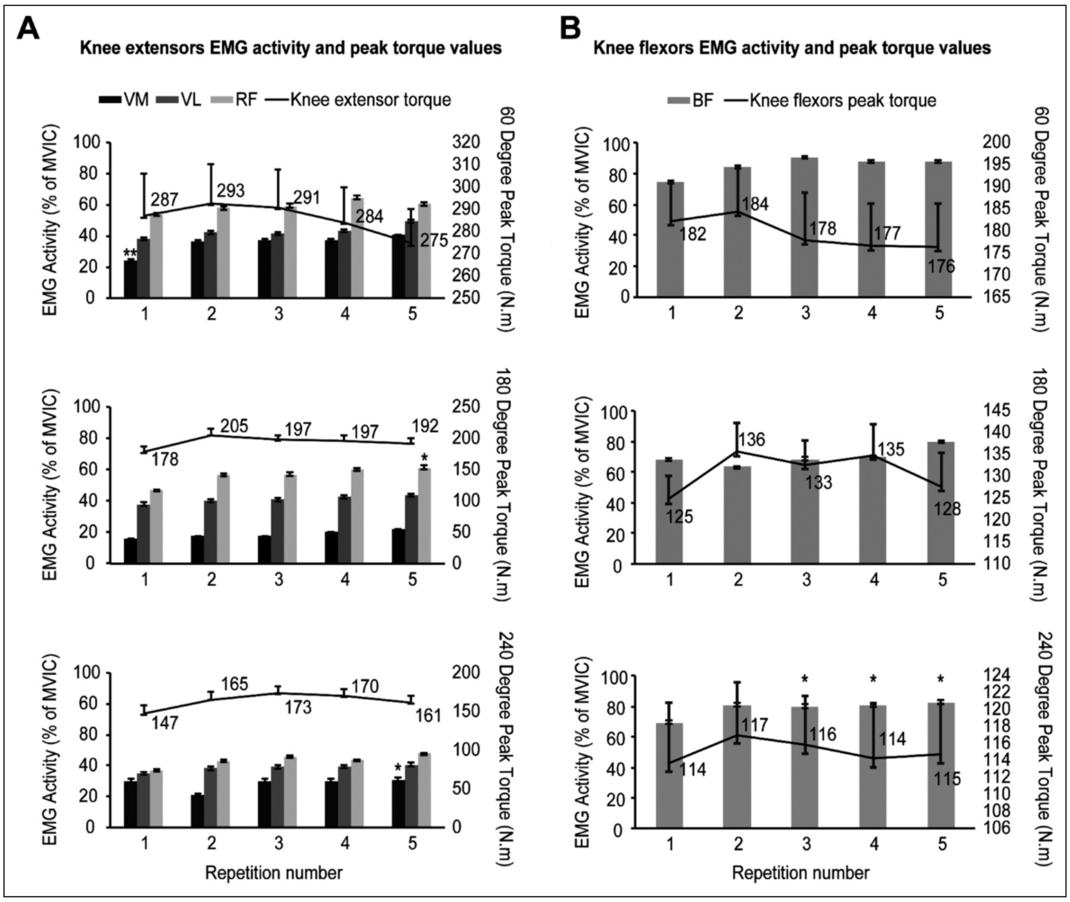

FIGURE 1: Peak Torque and EMG activity curves as a percentage of MVIC for the knee extensor (VM, VL and RF) and flexor muscle groups (BF) at each isokinetic angular velocity tested (60°/s, 180°/s and 240°/s).

VM: Vastus Medialis; VL: Vastus Lateralis; RF: Rectus Femoris; BF: Biceps Femoris. p<0.05; p<0.001.

There is a negative correlation between RF muscle activation and torque during the first maximum isokinetic CON contraction at an angular velocity of 180°/s (first repetition: r= -0.539; p=0.070). During the third, fourth and fifth repetitions at an angular velocity of 240°/s, BF muscle activity was 80% that of the MVIC and the mean knee joint torque (for the last three repetition) was 115 Nm. A negative correlation was observed between BF muscle activation and torque during the third, fourth and fifth repetitions of the maximum isokinetic CON contraction at an angular velocity of 240°/s (third repetition: r= -0.618; p=0.043; fourth repetition: r= -0.568; p=0.069; fifth repetition: r= -0.605; p=0.048) (Figure 1).

The Vertical Jump Height, Maximum Power, Concentric and Eccentric Work, and Peak Anaerobic Power (PAP) values are shown in Table 4. Subjects produced significantly higher CMJ heights than SJ heights (10%) (p=0.028). Additionally, the maximum power of a CMJ was higher than that of an SJ (p=0.000), concentric work (p=0.001) and peak anaerobic power (p=0.020). Dynamometry showed no relationships between the heights of CMJ, SJ and peak torques at any angular velocities (60°/s, 180°/s, 240°/s).

Table 5 shows a negative correlation between body mass index (BMI) and jumping variables (CMJ, maximum power and concentric work).

DISCUSSION

This study generated extensive information on knee extensor and flexor muscle torques, muscle activation (EMG) and the different vertical jumping performance characteristics of male volleyball players.

TABLE 4: The results of vertical jump performance.

	Bosco (cm)	Maximum Power (w/kg)	Concentric Work (j/kg)	Eccentric Work (j/kg)	Peak Anaerobic Power (PAP) (W)
SJ	37.7±1.5	30.1±4.30	6.9±0.43	-	1324.2±92.9
CMJ	42.0±0.9	53.0±5.47	7.8±0.78	-3.2±0.4	1583.5±44.2
P	0.028	0.000	0.001	-	0.020

SJ: Squat Jump; CMJ: Counter Movement Jump. P<0.05; P<0.001.

One of the most commonly used methods of assessing the balance between antagonist and agonist muscle strengths is isokinetic testing.[26-28] Our isokinetic testing protocol measured the H:Q ratios of the peak torques of maximal CON contractions of the hamstrings and quadriceps. Our principal finding is that angular velocity increases (60º/s, 180º/s and 240º/s) as the maximal torque value decreases. Similarly, Cheung et al. study of torque from the contraction of agonist and antagonist muscles around the knee joint supports our results.[29] In agreement with previous reports, we found that knee extensor torques were higher than flexor torques for all angular velocities tested.[30,31] Hadzic et al. reported that the knee extensors are maximally active during landing (deceleration and the control of knee flexion while working eccentrically) and during the take-off phase of the jump, while intermediate activity was observed during the amortization phase of the jump.[31] The concentric Q and H muscle torques of the Turkish male volleyball players in our study are higher than the corresponding values observed in elite Slovenian volleyball players at the same league level.[31]This variation in muscle torque response could reflect differences in subjects' heights and body masses, which vary considerably between volleyball players. For example, the average heights and weights of the Turkish volleyball players are 178±4.97 cm and 72.44±6.76 kg, compared with 188.0±7.3 cm and 81.5±9.2 kg for the Slovenian players. We found a statistically significantly relationship between CMJ height and BMI, maximum power and concentric work. A lower BMI could be advantageous for the maximum power, concentric work and CMJ height performance variables. Many studies have addressed the physiological and biomechanical determinants of a vertical jump.[32,33] Most emphasize the relationship between anthropometric factors and vertical jump heights, in agreement with our findings.

TABLE 5: Pearson correlation coefficients between BMI and jumping variables

	CMJ (cm)	Maximum Power (w/kg)	Concentric Work (j/kg)
r	-0.670	-0.747	-0.676
p	0.017	0.005	0.016

p<0.05.

BMI: Body mass index; CMJ: Counter movement jumping.

The H:Q ratio is also important for volleyball performance and is a goal during rehabilitation because the flexor-extensor strength balance is important for the overall stability of the knee.[34] Published H:Q ratios range from 0.5 to 0.8.[35,36] Harter et al. suggested that the H:Q ratio should approach 1.0 because the increased functional capacity of the hamstrings increases the dynamic stability of the knee joint.[37] Athletes with a concentric H:Q ratio closer to 1.0 may have a reduced risk of hamstring strain.[38] Additionally, athletes with Anterior cruciate ligament injuries and a concentric H:Q ratio closer to 1.0 may have a reduced risk of an anterolateral subluxation of the tibia.[27] As previously stated, an H:Q ratio of 1.0 indicates perfect coactivation of the hamstrings and quadriceps, as is optimal for the dynamic stabilization and protection of the knee during sport. The average H:Q ratios obtained from the volleyball players we studied fell in the range of 0.5-0.8. Moreover, the H:Q ratio increased in parallel with the angular velocity (H:Q ratio for 60°/s: 0.65±0.65; for 180°/s: 0.69±0.14 and for 240°/s: 0.72±0.18), which is in agreement with previous studies.[29,31,34,39]

The second aim of this study was to determine the relationship between maximum isokinetic concentric knee torques and EMG activity. Adding

EMG data to the evaluation of muscular activity during maximal isokinetic performance could provide more accurate results and could optimize the testing and training of volleyball players. Our EMG and torque recordings indicated that knee flexor muscles (BF) have greater EMG activity than the knee extensor muscles (VL and VM), while the EMG activity of the RF and BF muscles did not differ significantly. We believe that muscle architecture likely accounts for these results. The quadriceps muscles (VL, VM, RF and Vastus Intermedius) are predominantly monoarticular (except for the RF), but the hamstrings (BF, semitendinosus and semimembranosus) are biarticular.[40] Hip flexion therefore causes less passive stretch for the quadriceps and, consequently, less torque during knee extension. Similarly, previous EMG studies have shown a change in the activation level of each muscle part accompanying a change in the strength intensity level, the joint angle (total muscle length), the shortening velocity or the contraction type.[41-43] Our study showed that, during successive maximal isokinetic CON contractions, the EMG activity of the knee extensors and flexors increased. Previous studies indicated that muscles maintain a constant force in the face of fatigue, at least in part by recruiting additional motor units, and that this can increase EMG amplitude.[44,45] In addition, Adam and De Luca reported that the recruitment threshold of motor units declined throughout a series of contractions.[45]

Different angular velocities (60°/s, 180°/s, 240°/s) affect torque responses in an isokinetic test. The extensor and flexor muscles of volleyball players have lower EMG activities and higher knee joint torques when contractions start at lower angular velocities (60°/s). An attempt to recruit slow twitch motor units to contribute to muscular contractions could account for this reduced EMG amplitude. In response to the higher angular velocity (240°/s) experienced at the end of contractions, the volleyball players' extensor and flexor muscles exhibited higher EMG activity and lower knee joint torque. In addition to leg muscle fatigue, the average firing rates for the higher threshold motor units never equaled those of the first motor units to be recruited. The conduction velocity of the fatigued muscle decreased and the EMG amplitude increased. Early fatigue of leg flexors can account for the increase in the amplitude of the force twitches of motor units during isokinetic contractions.

Other findings in our study indicate that the CMJ height (42.00±0.96 cm) is significantly greater than the SJ height (37.72±1.53 cm). Previous studies have established that subjects perform better on tests of CMJ than SJ.[7,46,47] Elite Portuguese female volleyball players' CMJ ranged from 34.2±5.9 to 35.6±6.3 cm while their SJ ranged from 27±2.5 to 32.7±4.0 cm (Marques et al., 2008). The CMJ and SJ of a male Spanish national volleyball team ranged from 46.5±3.5 to 49.7±4.6 cm and 43.9±5.0 to 47.9±4.0 cm, respectively, across competitive seasons.[47] The CMJ and SJ of professional team members who played in the Brazilian Volleyball Super League were 48.38±3.96 and 45.30±4.07, respectively.[4] Elite adolescent volleyball players had CMJ and SJ heights of 33.47±6.11 and 31.68±5.96.[48] Explanations for the differences between CMJ and SJ heights could include the following: (a) volleyball players' lack of experience performing SJs may make them unable to properly control this type of jump and unable to effectively transform the work of their muscles into effective energy (i.e., energy contributing to jump height); (b) muscles are unable to achieve a high level of force prior to the CON contraction in SJ;[47] (c) during the countermovement before CMJ, muscles are pre-stretched and release their absorbed energy in the jump phase, when the muscles act concentrically and can produce more work;[49] and (d) muscle stretching in the countermovement of a CMJ triggers spinal reflexes in addition to longer-latency responses that together increase muscle stimulation during the concentric phase. This increases the force and the work available for the concentric phase in CMJ that is lacking during SJ, where there is no pre-stretch phase.[49] In addition to these possible physiological explanations, differences in competitive level, physical attributes, sport discipline, genetics, training status and gender can also affect performance in CMJ and SJ tests.

We found no relationships between CMJ and SJ heights and peak torques at any angular velocities (60°/s, 180°/s, 240°/s) as measured by isokinetic dynamometry. Previous studies found relationships between strength and jumping variables that were either low to moderate or not significant.[50-52] These contrasting findings can be explained by differences in the (i) characteristics of the sports; (ii) training periods and levels; (iii) isokinetic testing protocols; and (iv) methods and exercises for assessing muscle strength (OKC and CKC) used in various studies. Our use of the OKC isokinetic test of muscle strength is a possible explanation for the absence of a relationship between isokinetic strength and jumping height in our study.

Iossifidou et al. showed that there are important differences in muscle activation and knee joint power development that must be taken into consideration when isokinetic tests are used to predict jumping performance.[53] While vertical jumping as a stretch-shortening cycle type motion is a CKC isokinetic exercise employing the constant angular velocity of a machine that involves only one segment and one joint is an OKC exercise.[8,54] The squat vertical jump test, in contrast, involves both legs and is a CKC exercise with different muscle activation patterns, where the knee's angular velocity is not limited and energy is transferred between joints.[53] An isokinetic exercise would not be sufficiently movement-specific to predict jumping performance.

While the jumping test specifically measures the anaerobic power of volleyball players, their ability to generate power may be quite different when other methods are used. Anaerobic power and capacity are high in anaerobic sports such as volleyball.[55,56] We measured PAP by a vertical jump because jumping performance is a CKC exercise. Our results show that concentric work (CW), maximum power (MP) and PAP in a CMJ are higher [(CW: 7.76±0.78(j/kg); MP: 53.00±5.47(w/kg); PAP: 1583.54±44.23(W))] than in an SJ [(CW: 6.87±0.43 (j/kg); MP: 30.06±4.30 (w/kg); PAP: 1324.18±92.94 (W)]. The PAP levels we found are higher than those reported by Popadic Gacesa et al.[57] Differences in the PAP assessment methods used or the BMIs of volleyball players in our studies may account for this discrepancy.

CONCLUSION

We investigated the knee extensor and flexor muscle torque, EMG activity and different vertical jumping performance characteristics of male volleyball players. Our conclusions can be summarized as follows:

1. The greatest H:Q ratios were obtained at an angular velocity of 240º/s. Isokinetic tests at this velocity may best distinguish H:Q differences among volleyball players.

2. The differences in EMG activity between knee extensors (VL, VM) and flexor muscles (BF) during isokinetic testing, except for RF, are consistent with muscular architecture and could be related to changes in strength intensities, joint angles (total muscle length), shortening velocity or type of contraction.

3. With repeated maximal isokinetic CON contractions, the EMG activity of the knee extensor and flexor muscles increases, perhaps due to muscle fatigue.

4. Subjects' CMJ height, maximum power, concentric work and peak anaerobic power were significantly higher than their SJ height. This difference may arise from differences in the energy contributing to jump height.

Future studies should focus on OKC and CKC exercise tests to assess muscle strength. Additionally, muscle strengthening exercises should employ both isokinetic (OKC) and plyometric (CKC) exercises. To increase the balance of strength between the hamstring and quadriceps and to decrease the risk of knee injury, it can be recommended that volleyball players and coaches focus on hamstring muscle exercises.

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