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Relationship Between Peak Torques of Lower Extremity Muscles with Anterior Knee Shearing Force During Single-Leg Drop Landing

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Abstract: The purpose of the present research was to study the relationship between peak torques of lower extremity muscleswith anterior knee shearing force (AKSF) during single-leg drop landing.22healthy male student athletes voluntarily participated in the research. The peak torque of the quadriceps, hamstring and soleus of the subjects was measured using Biodex Isokinetic System. Then the subjects were asked to perform single-legdrop landingfroma box 30 cm in height placed at a 15-cm distance from a force plateand to jump at its center while the data were collected by the force plate during landing. The peaktorques of lower extremity musclesand the peakposterior ground reaction forcewere normalizedto the body weight of the subjects. The peak posterior ground reaction force (GRF) was considered equivalent toAKSF and loading on the ACL.Data were analyzed using Pearson's correlation coefficient and multivariate regression. Results revealed a significant relationship between quadriceps ($r = 0.68$), hamstring ($r = -0.79$) and soleus-to-quadriceps peak torque ratio ($r = -0.64$) with AKSF at $P \leq 0.05$ significance level. In the third predictor model, using multivariate regression ($R^2 = 0.834$, $\beta_Q = 0.50$, $\beta_H = -0.48$ and $\beta_S = -0.26$), the variables of hamstring,quadriceps and soleus peak torque were significant ($F_{3,18} = 30.90$, $P = 0.0000$). Considering the results of the research, during single-leg drop landingthe hamstring acts asthe muscle reinforcing the ACL (agonist tothe ACL) and the quadriceps acts as the muscle generating force on the ACL (antagonist tothe ACL). Moreover, the soleus works in conjunction with the hamstring as an agonist tothe ACL.

Key words: Lower Extremity Muscle Torque · Anterior Knee Shearing Force · Single-Leg Drop Landing, Anterior Cruciate Ligament

INTRODUCTION

The biomechanics of anterior cruciate ligament (ACL) has been studied from different perspectives such as anatomical observation, mathematical modeling, ACL force measurement and ACL displacement measurement [1-5]. Various theories account for the etiology of ACL injuries which can be categorized into intrinsic and extrinsic factors. The intrinsic factors include narrow intercondylar notch, a weak ACL, generalized physiologic laxity, hormonal influences andmalalignment of the lower extremity. The extrinsic factors include abnormalquadriceps and hamstring interactions, altered neuromuscular control, shoe-surface interaction, playing surface and athlete's playing style [6].

The posterior ground reaction forces (PGRF) during landing are employed as estimates of knee sagittal planestability [7, 8] and can be considered as equivalent to AKSF and loading on the ACL. ACL injury mechanisms can be categorized into contact which happen due to physical contact between an object ora personand the athlete and non-contact in which no physical contact with the athlete takes place at the time of injury [6]. Almost 70-90% of ACL injuries is related to

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sports and happens through the non-contact mechanism [2, 4, 6, 9, 10]. Although landing and/or deceleration before a changein direction (what happens in sports such as basketball, handball and volleyball) are cited when discussing non-contact ACL injury mechanisms [2, 4, 6], studying these mechanisms and identifying their various dimensions are still of interest of researchers.

There have been many research studies regarding the role of leg muscles inthe anteriortranslation ofthe tibia relative tothe femur and loading on the ACL; yet the main focus has been on the quadriceps and hamstring [11-14].Muscles which,through contraction, dynamically prevent anterior proximal tibial translation relative to the femur and the consequent loading on the ACL act as agonists to the ACL, while the muscles which, through contraction, dynamically lead to anterior proximal tibial translation relative to the femur act as antagonists to the ACL [15]. Contraction of the agonist musclestakes the pressure off the ACL, while the contraction of the antagonist muscles leads to loading on the ACL. Most studies have mentioned the quadriceps as the antagonist and hamstring as the agonist to ACL [11-14]. Most studies carried out on the role of lower extremity muscles in the amount of loading on ACL have come to the conclusion that during landing, the hamstring pullstheproximal tibia posteriorly through its contraction and takes the load off the ACL and it has been referred to as the antagonist to ACL [11-13]. In addition, most studies carried out in this field suggest that during landing, since the quadriceps deceleratesthe body due to its eccentric contraction, itproduces an anterior shearing force on the proximal tibia via the patellar tendon and thus places a strain on the ACL and it has been suggested to act as the antagonist to the ACL [11, 12, 14]. It has also been cited in another study that the quadriceps protects the ACL while performing closed kinetic chain activities [16].

Recent researches have shown that calf muscles are involved in the activities that place the ACL at the risk of rupture, such as cutting movements and landing from a jump [17]. Studies carried out on the role of posterior calf muscles in loading on the ACL have concluded that in closed kinetic chain activities, the soleus prevents the loading on the ACL and the gastrocnemiusplaces strain on it. Elias *et al.* [15] studied the effect of isolated activation and co-activation of the soleus and the gastrocnemius in order to determine the effect of simulated contraction of these muscles on the tibiofemoral joint and showed that the soleus acts as an agonist and the gastrocnemius acts as an antagonist to the ACL [15]. Another interesting result of this research was the anterior translation of the tibia (i.e. loading on ACL) during the co-contraction of the soleus and the gastrocnemius. Fleming *et al.* [18] studied the ACL strain response due to isolated contraction of the gastrocnemius muscle to determine how these strains are affected by the co-contraction with the hamstrings and quadriceps muscles using electrical muscle stimulation. They reported that the isolated contraction of the gastrocnemius and its co-contraction with the quadriceps and the hamstring produce ACL strains that are higher than those produced by the isolated contraction of the hamstring [18]. In another study, Sherbondy*et al.* [19] studied the effect of simulated contraction of posterior calf muscles during passive ankle dorsiflexion on the anterior translation of the tibia in subjects with healthy and injured ACL as well as on cadaver knees and they introduced the posterior calf muscles as dynamic knee stabilizers.

Extortionate costs are paid for recovery or rehabilitation from ACL injuries [20] and in addition the possibility of suffering joint diseases (e.g. osteoarthritis) remains even after the recovery and rehabilitation of the knee [21, 22]. Considering the extant literature, it seems that during landing the soleus, in concert with the hamstring, can play an important role in reducing loading on the ACL and a higher soleus-to-quadriceps peak torque ratio can be effective for reducing the possibility of ACL injuries. Thus, the purpose of the present research was to study the relationship between peak torques of lower extremity muscleswithAKSF during single-leg drop landing.

MATERIALS AND METHODS

The present research was correlational ones. 22 subjects with mean and standard deviation of 22±3 years of age, 75.89±3.22 kg of mass and 177.84±4.52 cm of height voluntarily participated in this study. Quadriceps, hamstring and soleus peak torqueswere measured using the Biodex Isokinetic System at the angular speed of 60°/s. To measure peak muscle torque, the subject sat on the chair of the Biodex System and was fastened from above the joint of interest with special straps so that the agonist muscles of the other joints would not be used while performing the movements. The subjects were verbally encouraged for exerting maximum power. The subject performed each movement three times and the highest generated torque was recorded as their peak muscle torque. The data obtained from the Biodex System was normalized to the body weight of the subjects. The subjects stood barefoot on a 30 cm in height placed at a 15-cm distance from a force plate that was regarded as the landing surface. The subjects were familiarized with all the instructions of the landing protocol before performing the test. The subjects stood on the box in a relaxed state, bearing the whole body weight, standing on both legs with their hands on their hip, while they were instructed to jump from the box and perform single-leg drop landing on the force plate. The subjects were asked to try controlling their balance after landing on the force plate. The subjects were allowed to practice landing as many times as they wished in order to feel comfortable during the test and as well for the experimenter to determine their preferred leg. The preferred leg was considered as the leg on which the subjects mostly landed during the first three trials. Then the subjects performed the landing test and three of their acceptable attempts were recorded. The acceptable landing involved the initial contact of the forefoot, maintaining balance, ability to land without any short bounces and a knee flexion less than 90° [23].

The data related to single-leg landing was collected using the force plate system at a sampling rate of 200Hz. To prevent the overlapping of frequencies, the sampling frequency in the Fourier transformation must be at least two times greater than the maximum frequency of single-leg drop landing maneuver; since the raw signals in single-leg drop landing maneuver is less than 30Hz, the minimum sampling frequency for data collection is considered as 60Hz. The point of peak posterior GRF is a key point in single leg drop landing and the data related to it were further evaluated after being collected. At very low sampling rates the point of peak posterior GRFmay not be recorded and thus lead to incorrect calculations. Therefore, the sampling rate was chosen as 200Hz for collecting the GRF data.

Maximum GRF in the posterior direction was normalized to the body weight of the subjects and it was considered as the AKSF [7,8]. Descriptive statistical methods, Pearson's correlation coefficient at $\alpha \leq 0.05$ significant level and stepwise multivariate regression models were used to identify the relationship between peak lower extremity muscle torque and the amount of loading on the ACL. Multivariate regression is a statistical method which allows for predicting one's score in a variable based on their score in several other variables. There are different ways for determining the relative contribution of each of the predictor variables. In the stepwise method, the sequence for incorporating the predictor variables into the model (or removing them) is determined based on the strength of their correlation with the criterion variable. Each of the variables are incorporated into the model accordingly and its value is then determined. If adding a variable contributes to the model, it will stay in the model but in this condition, all the remaining variables in the model will be retested to determine whether they are still contributing to the success of the model and they are removed if otherwise.

RESULTS

Table 1 presents the descriptive statistical data related to the predictor variables (quadriceps, hamstring and soleus muscle torque as well as the soleus-to-quadriceps torque ratio) and the criterion variable (peak posterior GRF).

The correlation between quadriceps, hamstring and soleus muscle torque as well as the soleus-to-quadriceps torque ratio with peak posterior GRF presented in Table 2.

As can be seen, there is a high correlation between the variables of quadriceps, hamstring and soleus-to-quadriceps peak torque ratio and peak posterior GRF at $P \leq 0.05$, while there is no significant relationship between soleus peak torque and peak posterior GRF.

The results related to the relationship between the independent variables (quadriceps, hamstring and soleus muscle torque and soleus-to-quadriceps torque ratio) and

Table 1: Descriptive statistical data related to quadriceps, hamstring and soleus muscle torque as well as the soleus-to-quadriceps torque ratio and peak posterior GRF

	Muscle peak torque (N.m)				
Variable	Quadriceps	Hamstring	Soleus	Soleus/Quadriceps ratio	$F_x$max (N/BW)
Mean	0.018 ± 0.003	0.010 ± 0.002	0.004 ± 0.001	0.242 ± 0.084	0.296 ± 0.130

Table 2: Correlation between quadriceps, hamstring and soleus muscle torque as well as the soleus-to-quadriceps torque ratio with peak posterior GRF

	Peak torque of muscle			
Parameter	Quadriceps	Hamstring	Soleus	Soleus/Quadriceps ratio
Correlation with $F_x$max	0.679*	-0.794*	-0.422	-0.642*

*$P \leq 0.05$

the dependent variable (peak posterior GRF) as well as determining the independent variables that has the greatest effect on the dependent variable were identified using stepwise multivariate regression model and three predictor models were specified as follows:

In the first predictor model, R^2 was calculated as 63% suggesting that 63% of the changes in peak posterior GRF are related to the changes in hamstring peak torque. The adjusted R^2 which indicates the power of themodel is equal to 0.61 and ($F_{1,20}$ = 34.20, P = 0.0000). The only significant variable in this predictor model was hamstring peak torque (β = -0.79, P = 0.0000). The beta coefficient indicates that the ratio of the changesin hamstring peak torque to maximum posterior GRF is equal to -0.79.

In the second predictor model, R^2 was calculated as 78% suggesting that 78% of the changes in peak posterior GRF are related to the changes in quadriceps and hamstring peak torque. The adjusted R^2 which indicates the power of the model is equal to 0.76 and ($F_{3,19}$ = 33.79, P = 0.0000). The beta coefficient in this model is 0.42 for the quadriceps peak torque at P = 0.002. This result indicates that the ratio of the changesinquadriceps peak torque to maximum posterior ground shear force is equal to 0.42. Moreover, the value of beta for hamstring peak torque is -0.62 at P = 0.000, indicating that the ratio of the changes in hamstring peak torque to maximum posterior GRF is equal to -0.62.

In the third predictor model, R^2 was calculated to be 83% suggesting that 83% of the changes in maximum posterior GRF are related to the changes in quadriceps, hamstring and soleus peak torque. The adjusted R^2 which indicates the power of the model is equal to 0.81 ($F_{3,18}$ = 33.79, P = 0.0000). The beta coefficient in this model is 0.42 for the hamstring peak torque at P = 0.001 indicating that the ratio of the changes in hamstring peak torque to maximum posterior GRF is equal to -0.48. The value of beta for quadriceps peak torque is 0.50 at P = 0.000, indicating that the ratio of the changes in quadriceps peak torque to maximum posterior GRF is equal to -0.50. Moreover, beta coefficient for soleus peak torque is -0.26 at P = 0.027, significance level indicating that the ratio of the changes in quadriceps peak torque to maximum posterior GRF is equal to -0.26.

DISCUSSION AND CONCLUSION

The purpose of the present research was to study the relationship between peak torques of quadriceps, hamstring, soleus and soleus-to-quadriceps and AKSF during single-leg drop landing. The results revealed a significant correlation between quadriceps, hamstring and soleus-to-quadriceps peak torque withAKSF, while no significant relationship was observed between soleus peak torque and AKSF.

The positive correlation between quadriceps peak torque and AKSF (r = 0.68) indicates that AKSF increases with increase in quadriceps peak torque during single-leg drop landing. The negative correlation between hamstring peak torque and AKSF (r = -0.79) indicates that AKSF decreases with increase in hamstring peak torque during single-leg drop landing. Further, the negative correlation between soleus-to-quadriceps peak torque ratio and AKSF (r = -0.64) indicates that AKSF decreases with increase in soleus-to-quadriceps peak torque ratio during single-leg landing.

In the three predictor models defined usingstepwise multivariate regression, the inverse relationship between AKSF and hamstring peak torque is may be due to the ability of this muscle to exert posterior strain on the proximal tibia in all the flexion angles. Anatomically, the long heads of the hamstringare attached to theischial tuberosity and the short heads of the hamstringare located on the posterior part of the tibia. During landing, this muscle acts as an agonist to the ACL and by exerting force to the back of the proximal tibia leads to a decrease in the posterior force on the tibia. This decrease in the force moderates the loading on ACL and protects this ligament against rupture [11-13, 24]. The result of the present research regarding the effect of the hamstring role on AKSF and decrease in loading on the ACL is similar to the results of previous research [11-13, 24] and indicates that increased hamstring peak torque may reduce the possibility of injuries to the ACL during single-leg drop landing.

In the second predictor model (R^2 = 0.78, β_H = -0.620 and β_Q = 0.424), 78% of the changes in AKSF was determined by the changes in quadriceps and hamstring peak torque. Considering the beta coefficients, this finding suggests that the effect of the hamstring on AKSF is greater than that of the quadriceps. The reason for the effectiveness of the quadricepsand the hamstring in this predictor modelcan be interpreted as the major role of these two large muscles in moderating the knee forces during dynamic activities. As discussed earlier, one of the reasons for more ACL injuries among women can be their quadriceps-dominant pattern. This pattern is an imbalance between employing the quadriceps and the hamstring. Female athletes with a dominant-quadriceps pattern tend to increase knee extensor than knee flexor torques in activities that produce a high level oflower extremity joint torque [25]. Chappell *et al.* [26] reported that increased anterior shearing forceexhibited by female athletes is potentially the result of greater quadriceps force, less hamstring force and less knee flexion [26]. In low knee flexion angles (0-30 degrees of flexion), contraction of the quadriceps pulls the tibia anteriorly and increases loading on the ACL [26]. In knee flexion angles less than 45°, the quadriceps is an antagonist to the ACL [26]. In knee flexion angles more than 45°, the quadriceps displaces the tibia in the posterior direction and decreases the loading on the ACL[27].

Yanagawa *et al.* [28] reported that the co-contraction of the hamstring and the quadriceps decreases the peak anterior translation of the tibia in both healthy and injured ACL groups [28]. The possible reason for the significance of the second predictor model can be that these two muscles, due to their co-contraction, can play an important role in decreasing the anterior translation of the tibia and loading on the ACL. Thus, these two muscles are introduced in the second predictor model as variables that have the greatest effect on AKSF. The results of the present research regarding the effect of the quadriceps and the hamstring on the AKSF and loading on the ACL is similar to the results of previous research [11-13, 24] and it can be inferred that the level of AKSF and consequently the loading on the ACL increases with quadriceps muscle torque during single-leg drop landing, whereby this muscle acts as an antagonist to the ACL; subsequently, with the increase in hamstring peak torque during single-leg drop landing, AKSF and as a result the loading on the ACLdecreases which identifies the possible role of this muscle as an agonist to the ACL.

In the third predictor model ($R^2 = 0.834$, $\beta_H = -0.48$, $\beta_S = -0.26$ and $\beta_Q = 0.50$) which was the best condition for the data analysis in the present research, 83% of the changes in AKSF was determined by the changes in hamstring, quadriceps and soleus peak torque. According to the beta coefficients, it can be concluded that the quadriceps has the greatest effect and the soleus had the least effect on AKSF.Since the soleus does not pass from the knee joint, its possible effect on the ACL strain is totally disregarded. Theoretically, with foot planted, the force exerted by the soleus, which resists the anterior rotation of the tibia on the knee joint,can reduce the anterior translation of the tibia relative to the femur.

Researches suggest that even in full extension the soleus generates a greater plantarflexion force in comparison with the gastrocnemius [29-31]. With the increase in knee flexion, the gastrocnemius shortens since the distance betweenits medial head on the posterior distal femur and its lateral head on the back of the calcaneus bone decreases. In contrast, knee flexion does not change the length of the soleus which passes only from the ankle joint. Muscle length affects its ability to generate contraction force. This phenomenon decreases the ability of the gastrocnemius for force generation along with knee flexion in comparison with the soleus [29-31].

Since the force of the quadriceps has anteriorcomponent acting on the tibia, the decrease in the quadriceps-to-soleus muscletorque ratio may increase the ability of the soleus for translating the tibia posteriorly. Since previous research has shown that the soleus tends to activate before the gastrocnemius during cutting and pivotingmovements[30],we believe that the early activity of the soleus during dynamic activities can be a mechanism for reinforcing the ACL.

Studies on dynamic balance can be divided intothe effect of co-contraction and isolated contraction of the muscle. In normal walking, the gastrocnemius and soleus are active from heel strike to the end of the stance phase.These muscles act eccentrically so as to reduce the translation of the tibia on the foot and to moderate ankle dorsiflexion. It is believed that the role of the soleus can be more important in walking, because its activity starts earlier and lasts longer than the gastrocnemius [31]. In addition, the soleus is larger and directly connects the tibia and the calcaneus. The gastrocnemius can only have 68% of the plantar-flexion torque generated by the soleus. Other calf muscles produce something between 1-6% of the torque produced by the soleus [31]. The possible reason for the significance of soleus peak torque in the third model and introduction of this muscle as a factor that affects AKSF may be due to the fact that thismuscle works in synergist with the hamstring in controlling the anterior translation of the tibia, especially at low knee flexion angles. As was mentioned earlier, the hamstring loses its mechanical advantage at angles close to full knee extension during landing and it cannot effectively influence the tibia. Since the soleus does not pass from the knee joint, its function does not change as a result of knee flexion conferring it an advantage in both knees; that is, the mechanical advantage of this muscle does not change with knee flexion angle. This suggested mechanism is similar to the isolated effect of the hamstring [31]. The results of the present research regarding the effect of the soleus on AKSF and loading on the ACL are consistent with previous research [15, 19, 32] and it can be inferred that with the increase in soleus peak torque in single-leg drop landing, AKSF and as a result the loading on the ACL decreases and this muscle acts as an agonists to the ACL.

Final Conclusion: Considering the results of the research, the hamstring along with the soleus moderates the anterior shearing force exerted on the tibia by the quadriceps and create a mechanism for preventing ACL injuries.

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