Original Research

Analysis of quadriceps muscles force and activity of a 3-Dimensional musculoskeletal model

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ABSTRACT

The purpose of this study was to determine the force of each component of the quadriceps muscles group in different exercises and to determine the activity ratio of vastus medialis to vastus lateralis. For this purpose, a 3-D model of the whole body was formed in the AnyBody Modeling System software. This model that had muscle only in the legs was sitting on the chair and was performed knee extension. Muscular modeling in this study was achieved by using a simple model of the muscles. After creating and uploading model in the software, inverse dynamic analysis carried out, and the force and activity of each quadriceps muscle component was obtained. The model was tested in three different conditions: (1) Not loading, (2) static training with maximum loading, (3) normal loading. Then the force and activity of each quadriceps muscles were examined in gait test. To do this, walking in AnyBody model was used. In each of these conditions, the force of each quadriceps muscle component and activity ratio of vastus medialis to vastus lateralis was calculated. According to the results, the rectus femoris muscle in not loading mode had the highest value (28%) in creating force. In the static, normal loading and walking conditions, vastus lateralis had the highest value in creating force that were 38%, 42% and 40%, respectively. The activity ratio of the vastus medialis to vastus lateralis in static training, normal loading and gait conditions were 0.92, 0.85 and 0.87 respectively which in static training had the highest value. The results showed that the force and activity charts of the vastus medialis, vastus lateralis and vastus intermedius had exactly similar pattern and they were different from the force and activity charts of rectus femoris muscle. In total, it seems that the results are acceptable in some analysis and are not in accordance with previous results in some others (i.e. not loading condition). Therefore, it is necessary to verify and assess the outputs after modeling in this software.

Keywords: AnyBody software, Quadriceps muscles, Knee joint, Modeling

Introduction

The quadriceps muscle group plays an important role in knee joint stability. The concentric action of this muscle group leads to extend the knee joint, which is a very important movement in producing power in lower limbs for any forward movement or body weight transfer. In addition, eccentric action of these muscles can cause rapid deceleration of knee joint flexion and continuously contract against gravity [1]. Weakness or strength imbalance in components of this muscular group can be associated with tribulation in daily life functions and sports activities, as well as many injuries in the knee joint. The quadriceps muscle strength seems to be a decisive factor in rehabilitating of the knee after knee ligament injuries [2]. It consists of four muscles that are the rectus femoris, vastus intermedius, vastus medialis, and vastus lateralis. The vastus lateralis is the largest and strongest muscle in the group [3]. In some publications, these two muscles also are divided into two vertical and oblique sub-branches, but there is a difference of opinion about independent existence of these sub-branches [4-9].

In the field of study on the quadriceps muscle activity, it seems that the first study of the functions of these muscles during exercise was done by Popok in 1963. He examined the activity of three superficial muscles of quadriceps during different exercises and recorded their electromyographic activities [10]. However, it seems that the articles in the field of the quadriceps muscles activities, more than other variables, have studied activity ratio of vastus medialis to vastus lateralis muscles, Because it has been suggested that these muscles have an important role in vulnerability of the patella to the medial or lateral, and the imbalance between the forces of these two muscles can cause the abnormal movement of the patella in femoral groove and resulting increase patellofemoral pain syndrome [11-13]. Also, other researchers have examined the activity ratio of vastus medialis to vastus lateralis muscles during different exercises of the quadriceps muscles [14-17].

In the field of geometrical analysis of the quadriceps muscles, Wilson and Sheehan (2009) determined the in vivo 3-dimensional (3D) measures of knee extensor moment arms, measured during dynamic volitional activity. The hypothesis was that the vastus lateralis (VL) and vastus medialis (VM) have significant off-axis moment arms compared to the central quadriceps components. After obtaining informed consent, three 3D dynamic cine phase contrast (PC) MRI sets (x,y,z velocity and anatomic images) were acquired from 22 subjects during active knee flexion and extension. Using a sagittal-oblique and two coronal-oblique imaging planes, the origins and insertions of each quadriceps muscle were identified and tracked through each time frame by integrating the cine-PC velocity data. They used this data to calculate the moment arm of each quadriceps muscle [18]. Wilson and Sheehan (2010) determined the dynamic line of action of the quadriceps muscles in a methodologically similar study of their previous research [19].

Simon et al (1995) calculated the knee joint torque from amount of muscle activity. In this study the relationship between activity of the muscles passing through the knee and knee torque was investigated [20]. Zhang et al (2003) studied the force distribution on the quadriceps components. They assumed that amount of transitional absolute torque of individual components of this muscles group increased by increasing total torque on the knee during knee flexion [21]. Elias et al (2006) compared the two methods used for determining the force distribution of quadriceps muscles on the individual components of these muscles. These two methods in this study included force distribution in terms of electromyographic activity and force distribution in terms of cross-section of these muscles [22].

In the most previous studies in the field of modeling quadriceps muscles, these muscles have been modeled as force lines or a constant force, which done due to the need of projects. Thus, the purpose of this study was to provide an accurate method to determine the force and activity of each quadriceps muscles components as well as muscle activity ratio of vastus medialis to vastus lateralis during different training conditions, without applying any simplifying assumption.

Material and Methods

Musculoskeletal Modeling

In this study, a three-dimensional model from the whole body was formed in AnyBody Modeling System software (Figure 1). This model has muscle only in the legs and the muscles of other parts of the body were not included. The model was sat on a chair while performing the extension motion of the knee. In order to apply a resistance force on the leg during its extension, a spiral spring was used. The spring was designed so that by moving the leg down, it applied a resistance force on the model through the model's sole of the foot. In this model, modeling of muscles was performed using a simple model. In the simple model of muscles, the relationship between the force and velocity is neglected. Nevertheless, the load and muscles directions is considered.

Loading & Model analysis

After creating and uploading the model to the software, the inverse dynamic analysis was carried out, and the force and activity of each quadriceps muscles components was obtained. It should be noted that this software uses optimization method with cost function of minimizing the maximum activity (fatigue criteria) to calculate muscular forces. The model was tested in three different training conditions and the force and activity values of the quadriceps muscles in each training conditions were recorded:

(1) Not loading: In this condition, the applied force to the leg through the soles of the feet was set zero. It represents the extension and flexion of knee in zero loading condition. In such condition, the only action that the quadriceps muscles do, is overcoming the moment caused by the weight force in order to extend the knee.
(2) Static training with maximum loading: In this condition, the torque of spring is increased so that the muscles of the quadriceps did not have the ability to open knee. Therefore, the quadriceps muscles in this case were set under static training condition and had highest rates of their activities.
(3) Normal loading: In this condition, the spring torque and applied load to the knee was kept in the 40% isometric condition and then extending movement of the knee was performed by model.
The total time of extension and flexion of the knee in each above condition was considered equal to 1 s that in the its first 0.2, the leg was moving towards the pedal and in the its last 0.2, the leg was moving away from the pedal, and there was no contact between the foot and pedal. The flexion angle of knee was decreased from 120° to 80° (extension of the knees) and then was increased from 80° to 120° (flexion of the knees).

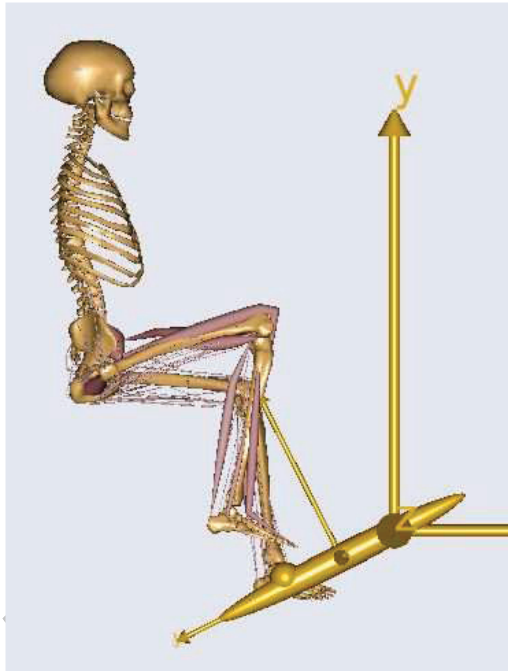

Figure 1. The model created in AnyBody Software.

After examining the force and activity of the quadriceps muscles in these three training conditions, these variables were studied also in gait test. To do this, the walking model in AnyBody software was used. To study the force and activity of the quadriceps muscles during walking, the simple model of muscles was also used. The kinematic data required for walking trial was adapted from the data provided by Wagen and collegiate. Determining the force and activity value of the quadriceps muscles in available software was done by using optimization and fatigue criteria [9].

Results

Phase one: unloading mode

In Figure 2, the activity of quadriceps muscles components including rectus femoris (RF), vastus intermedius (VI), vastus lateralis (VL) and vastus medialis (VM) in unloading condition is shown. It should be noted that the activity of a muscle in this software is defined as the ratio of generated force to the maximum force that can be generated in the maximum voluntary isometric contraction (MVIC). Therefore, the diagrams of forces have exactly the same pattern that only numeric values are differed by a factor.

Phase two: isometric mode

In Figure 3, the force of each quadriceps muscles components in this condition is shown. As mentioned before, at the first and last 0.2 s, there is no contact with the pedal. From 0.2 to 0.6 s, knee is extended and then knee is flexed again. As seen, the pattern of these diagrams is similar and therefore they can be utilized to estimate the force distribution in isometric mode. Also, we need activity diagrams to express the activity ratio of VM to VL which is shown in Figure 4.

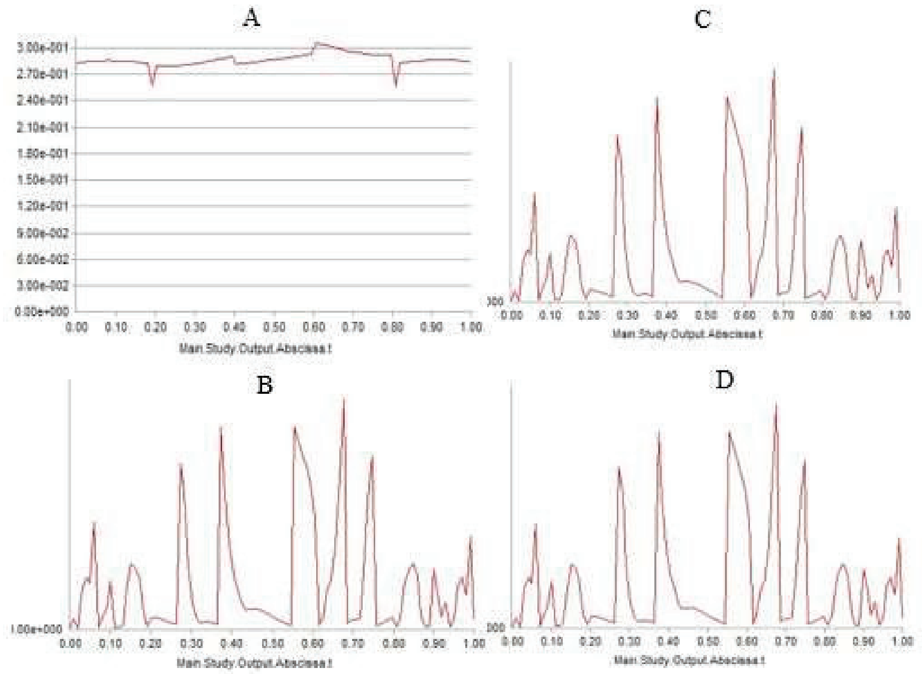

Figure 2. The activity of RF (A), VI (B), VL (C) and VM (D) muscles in unloading mode.

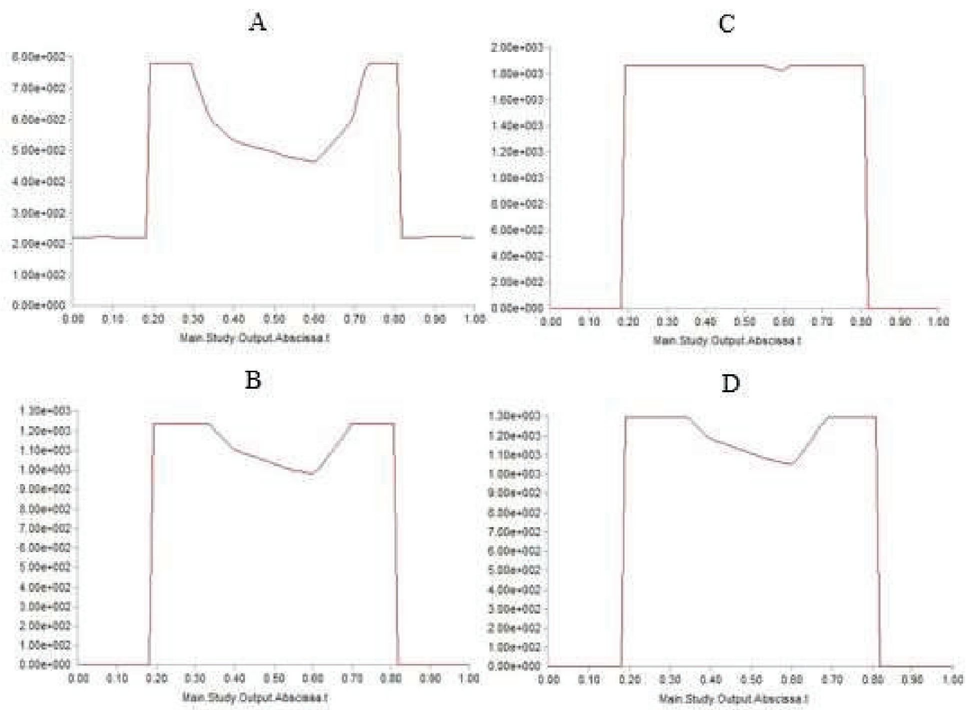

Figure 3. The force of RF (A), VI (B), VL (C) and VM (D) muscles in isometric mode.

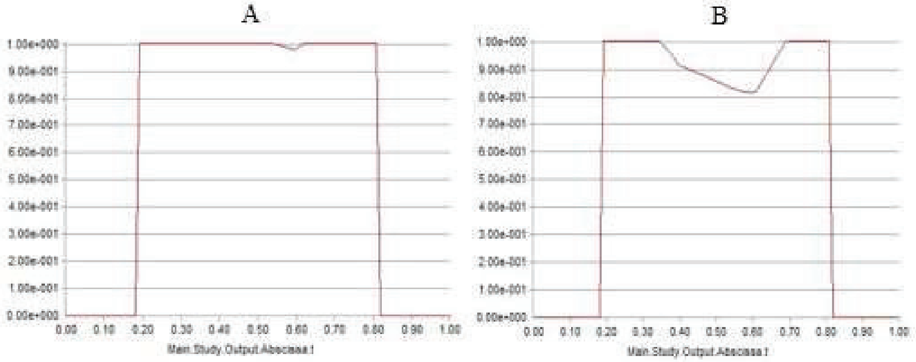

Figure 4. The activity of VL (A) and VM (B) muscles in isometric mode.

Phase three: normal loading

In Figure 5, the force of each quadriceps muscles components in normal loading is shown. Also, we need activity diagrams to express the activity ratio of VL and VM which is shown in Figure 6.

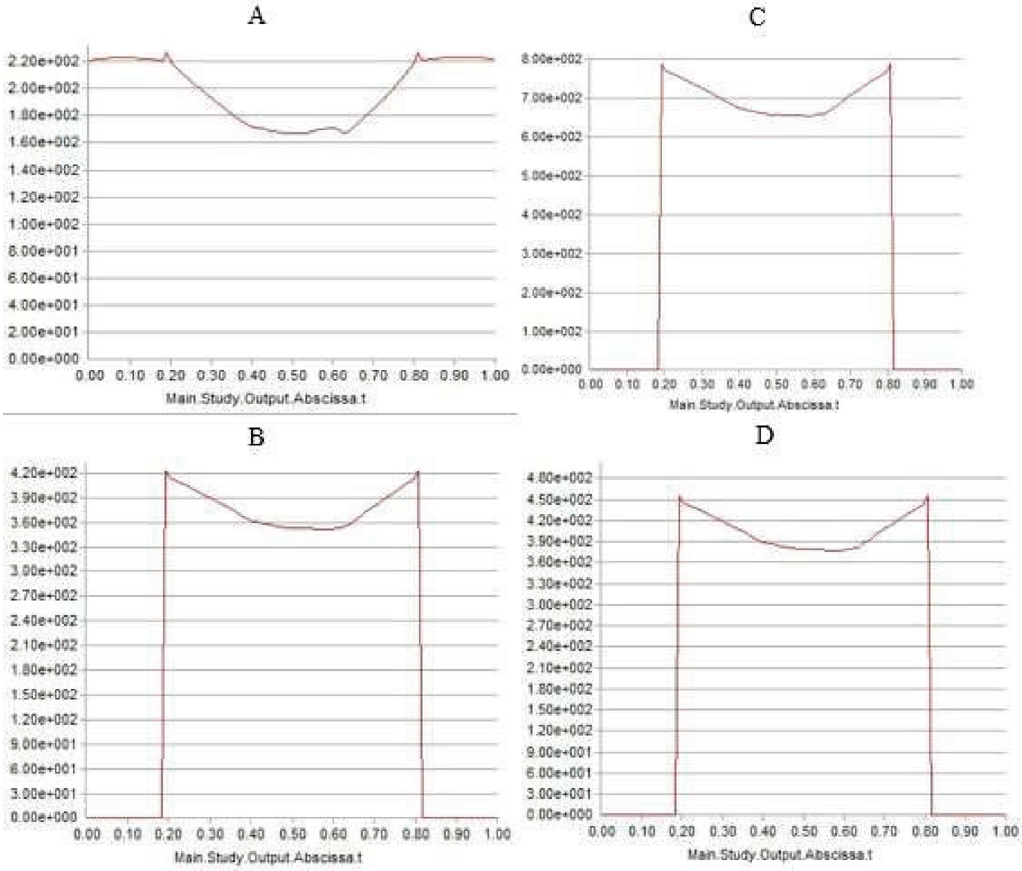

Figure 5. The force of RF (A), VI (B), VL (C) and VM (D) muscles in normal loading mode.

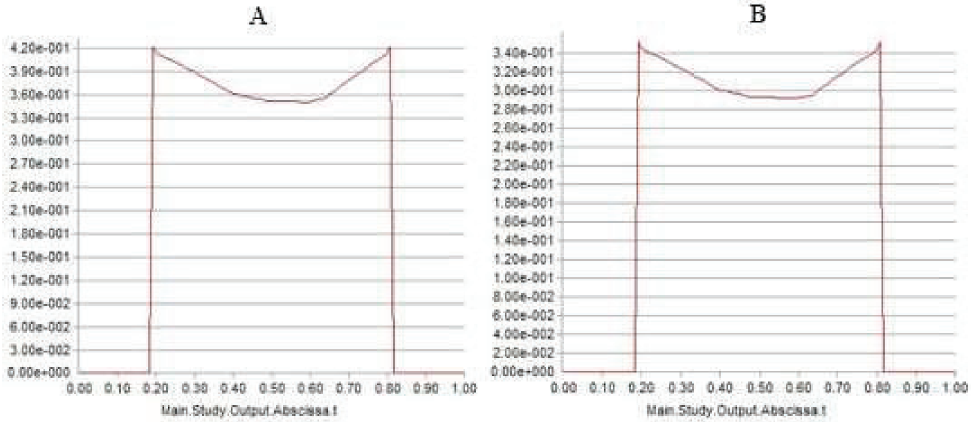

Figure 6. The activity of VL (A) and VM (B) muscles in normal loading mode.

Gait

In Figure 7, the force of each quadriceps muscles components in the gait mode is shown. Also, we need activity diagrams to express the activity ratio of VL and VM which is shown in Figure 8.

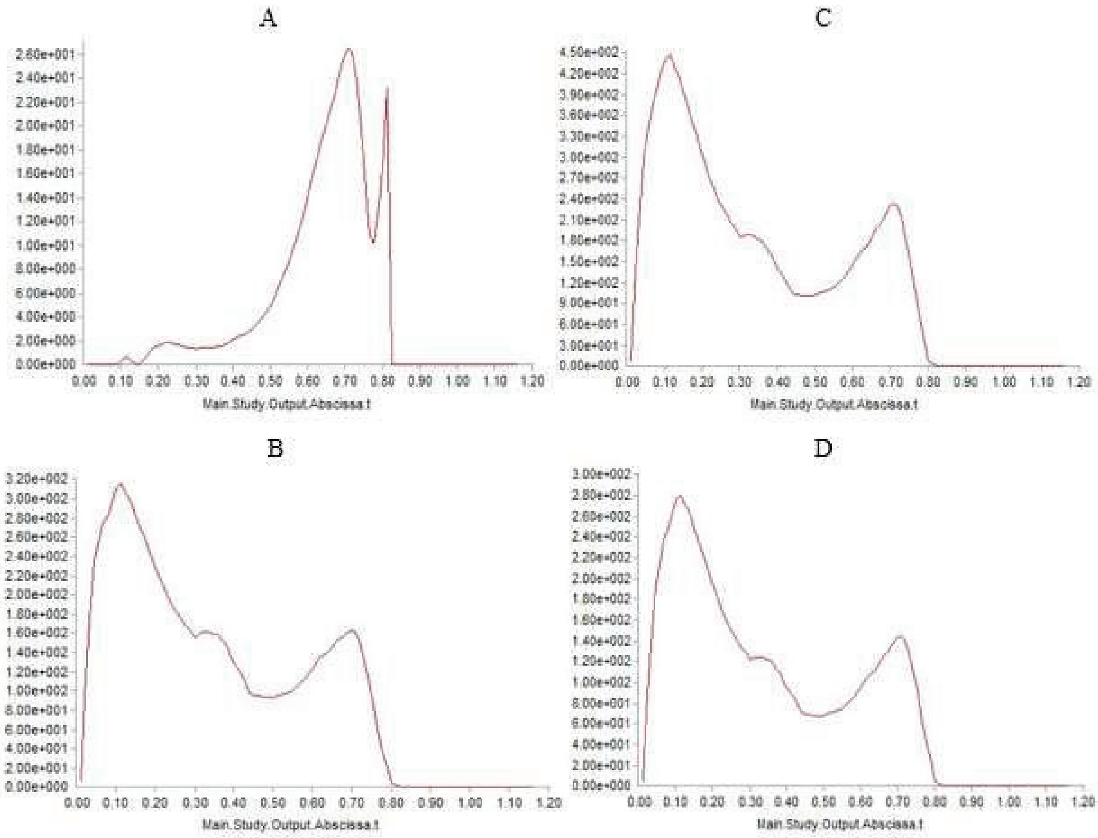

Figure 7. The force of RF (A), VI (B), VL (C) and VM (D) muscles in the gait mode.

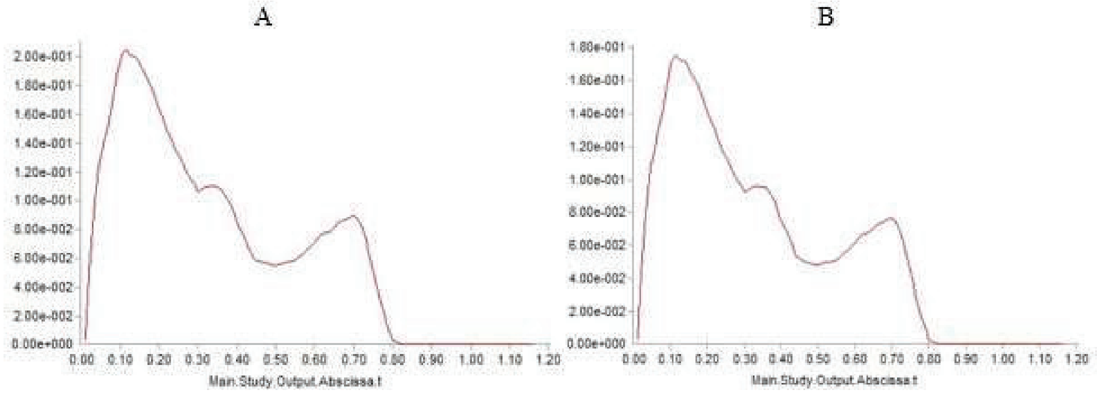

Figure 8. The activity of VL (A) and VM (B) muscles in the gait mode.

Discussion & Conclusion

The first phase (not loading):

In this phase, the diagrams show that the RF muscle endures the greatest force and has almost a constant activity. Interestingly, the maximum activity of this muscle in gait condition is less than the extension of knee without load. Other muscles also have an irregular and unmeasurable activity in this condition and their activity patterns are quite similar to each other. According to this, it seems that accuracy of the software and the implemented model in this condition is not acceptable and we should not use external force, even a very small amount, for examining the not-loading movement. Therefore, estimating the force distribution and activity ratio in not-loading state by using the data of this step does not seem logical.

The second phase (isometric):

As observed, before applying the spring force (from 0 s to 0.2 s), which is carried out the extension movement of the knee, the forces of all muscles (except RF) were zero. It shows that in not loading condition, almost all forces are tolerated by RF muscle. And then at moment 0.2 s in which spring force is applied, suddenly all the muscles reach to their maximum force. The force reduces gradually until moment 0.6s in which the knee continues to extend under the load. To provide a force distribution in this state, we ignored the value of not loading in which three muscles indicate zero and only RF muscle has nonzero value, because we will have a great error. Since there is a chart for each part not a single number, statistical works are used for reporting a number. For this purpose, we use the software data. AnyBody Software divides a 1-second interval into 100 points and records the forces values in every point to show graphically later. Therefore, the force ratio is calculated in each point. That means the force of a muscle is divided to the forces of four muscles and force ratios is obtained in each point. Then the average of these on 100 points was calculated and reported. The same thing is exactly done for computing the activity ratio of VM to VL. According to the above data, in isometric mode the force ratios (%MVIC) for RF, VI, VL and VM are as 0.13, 0.24, 0.38 and 0.25 respectively.

About the activity ratio of two muscles we can see from diagrams that VL muscle is at its maximum activity during almost all the time while the activity of VM muscle reduces gradually from its maximum (i.e.1) after moment 0.2s that even comes close to 0.8. Like the force distribution, if we want to provide a number as activity ratio of VM to VL in isometric condition, we will achieve 0.92.

The third phase (normal loading):

At this stage (40% of isometric condition), it is observed that the process of changing of the forces and activities is similar to isometric phase, but in general, there is less muscle activity. Again we see that before taking the leg to the pedal, only RF muscle indicates a nonzero force and by reaching the leg to the pedal and applying force from the spring, the force value of RF muscle decreases since other muscles have a nonzero value. Again, as above, after discarding the first and last 0.2 s, the force ratios for RF, VI, VL and VM are as 0.11, 0.23, 0.42 and 0.24 respectively. The activity ratio of VM to VL muscle in the normal loading condition is: 0.85.

The Gait:

According to the figures, it is observed that activity pattern of three vestus muscles (VI, VL and VM) are quite similar to each other and are quite different from the RF force pattern. Where these three muscles are in maximum force, the RF is in minimum and vice versa. The beginning moment of movement and recording the data is in accordance with the separation moment of the leg from the ground and beginning the walking cycle, therefore the force of each muscle at any time and at any point of the gait cycle can be expressed from the diagrams. Thus, in the gait condition, the force ratios (%MVIC) for RF, VI, VL and VM are as 0.01, 0.32, 0.40 , and 0.27, respectively. The activity ratio of VM to VL muscle in the gait condition is: 0.87.

Finally, it should be noted that because of AnyBody software is new and many errors occur during loading and such problems, more studies are needed to carefully examine models and desired conditions. For instance, instead of using simple single-force muscles can use a muscular model in which the force-velocity relationship also be considered. By using this model we can also examine the effect of different speeds of the knee motion that it was avoided in this research due to many errors and difficulties. In total, it seems that the results are acceptable in some analysis and are not in accordance with previous results in some others. For example, the predicted activity pattern in not loading condition is not acceptable compared with previous results. So, it is necessary to verify and assess outputs after modeling in this software.

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چکیده فارسی

تحلیل نیرو و فعالیت عضلات کوادریسپس با استفاده از یک مدل عضلانی اسکلتی سه‌بعدی

فرزام فرهمند، سید حسین حسینی و محمد مهدی سیفی

هدف از انجام این پروژه، تعیین میزان نیروی اجزای گروه عضلانی کوادریسپس در حالت های متفاوت تمرینی و نیز تعیین نسبت فعالیت عضله پهن داخلی به عضله پهن خارجی بود. به این منظور، یک مدل سه بعدی از کل بدن در نرم افزار AnyBody Modeling System تشکیل شد. این مدل که تنها در پاها دارای عضله بود، بر روی صندلی نشسته و حرکت باز کردن زانو را انجام می داد. مدلسازی عضلانی در این مدل با استفاده از مدل ساده عضلات صورت گرفت. پس از ایجاد مدل و بارگذاری در محیط نرم‌افزار، تحلیل دینامیک معکوس انجام پذیرفت و نیرو و فعالیت هریک از اجزای عضلات کوادریسپس به دست آمد. این مدل در سه شرایط متفاوت مورد بررسی قرار گرفت: (۱) بدون بارگذاری، (۲) تمرین ایستا با بارگذاری بیشینه، (۳) بارگذاری عادی. سپس نیرو و فعالیت هر یک از اجزای عضلات کوادریسپس در آزمایش گیت نیز بررسی شد. برای این کار از مدل راه رفتن موجود در AnyBody استفاده شد. در هر یک از این شرایط، نیروی هر یک از اجزای عضلات کوادریسپس و نیز نسبت فعالیت عضله پهن داخلی به عضله پهن خارجی محاسبه شد. بر اساس نتایج بدست آمده، عضله راست رانی در شرایط بدون بارگذاری از بیشترین سهم در تولید نیرو (۲۸٪) برخوردار بود. در شرایط ایستا، بارگذاری عادی و گام برداری، عضله پهن خارجی از بیشترین سهم در تولید نیرو برخوردار بود که میزان آن به ترتیب برابر ۳۸٪، ۴۲٪ و ۴۰٪ بود. نسبت فعالیت عضله پهن داخلی به پهن خارجی در شرایط تمرین ایستا، بارگذاری عادی و گام برداری به ترتیب ۰/۹۲، ۰/۸۵ و ۰/۸۷ بود که در شرایط بارگذاری بیشینه از بیشترین مقدار برخوردار بود. نتایج این تحقیق نشان می دهد که نمودارهای نیرو و فعالیت سه عضله پهن داخلی، پهن خارجی و پهن بینابینی در شرایط متفاوت تمرینی از الگوی کاملا مشابهی برخوردارند و متفاوت از نمودارهای نیرو و فعالیت عضله راست رانی می باشند. بطور کلی، به نظر می‌رسد که در بعضی تحلیلها نتایج قابل قبول است و در بعضی دیگر (برای نمونه در شرایط بدون بار) منطبق بر نتایج قبلی نیست. لذا لازم است که پس از مدل‌سازی در این نرم‌افزار، خروجی‌ها ارزیابی و درستی‌سنجی شوند.

واژه‌های کلیدی: عضلات کوادریسپس، مفصل زانو، نرم‌افزار AnyBody ، مدل‌سازی.