Biarticular Hamstring Muscles Can Act as Knee Extensors – A Computer Simulation Study

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Abstract

Purpose: It is unclear whether biarticular hamstring muscles (HAM) can act as knee extensors or not. The purpose of this study is to identify the conditions that HAM can act as a knee extensor by using a computational simulation approach.

Methods: The modified Gait2392 musculoskeletal model was used in this study. The posture was determined with a hip flexion angle that ranged from -30° to 90° and a knee flexion angle that ranged from -10° to 90° . The simulations were executed under two conditions: all segments are free to move, non-contact with the ground (nCG), and the foot is constrained on the ground, contact with the ground (CG). Induced acceleration analysis was applied to determine the contribution of the HAM to the knee angular acceleration.

Results: Three key findings were discovered. 1) HAM can act as knee extensors that have CG condition as well as nCG condition. 2) The HAM function changes depending on the posture. 3) The range of the hip joint that HAM was able to act as a knee extensor was expanded for the CG condition from the nCG condition.

Conclusions: We identified the situations in which HAM can act as knee extensors and demonstrated that the HAM function on the knee joint changes depending on the posture and the foot contact condition. Our findings suggest that HAM can be used as compensatory movement strategy for patients with a reduced capacity to generate knee extension if the patients have enough HAM strength.

1. Introduction

The capacity to generate knee extension during movement is one of the key factors in predicting movement, which includes locomotion velocity [1–3]. When knee extension is impaired because of some conditions, such as stroke patients and patients who have undergone partial or total quadriceps resection, decreasing the capacity to generate knee extension occurred. This causes abnormal knee motion during movement, genu recurvatum, and giving way. Weakness in the quadriceps muscles can cause abnormal knee joint movement during walking [4, 5]. The level of activity of daily living decreases when patients show abnormal knee motion during movement [3]. In almost all cases, it is impossible to fully recover the patient's capacity to generate knee extension [6–8]. Therefore, this is an important matter in terms of clinical rehabilitation in terms of improving the patient's capacity to generate knee extension.

There is a probability that biarticular hamstring muscles (HAM) can compensate for the decreased capacity to generate knee extension. Some researchers have provided the theoretical perspective that HAM can act as knee extensors [9, 10]. This theoretical perspective was supported by the findings of previous studies that showed the counterintuitive function of the biarticular muscles [11–14]. Meanwhile, other studies that investigated the HAM function in the knee joint have shown that HAM can act as knee flexors [15, 16]. Even though this point has been discussed since the 20th century (Lombard and Abbott, 1907), it is not clear whether HAM can act as knee extensors or only act as knee flexors.

To break such a stalemate, it is necessary to establish the theoretical framework of how and when HAM can act as knee extensors by considering the main contributing factors to determine the HAM function. Previous studies have identified two main factors that have contributed to this phenomenon. The first contributing factor is posture because the moment arm ratio and the intersegmental dynamics change depending on the posture. Many researchers have claimed that the biarticular muscle moment arm ratio of the proximal joint to the distal joint is the largest contributor to the counterintuitive muscle function [9, 17, 19, 21]. In addition, some studies have demonstrated that changes in the muscle function are caused by posture-dependent intersegmental dynamics [14, 15, 18, 22]. The second contributing factor is the foot contact condition. A number of previous studies have reported that whether the foot is in contact with the ground or it does not change the exerted muscle function [15, 17, 23]. Even though these contributing factors have already been identified, to the best of our knowledge, there have been no comprehensive studies to investigate the mechanics of how the counterintuitive biarticular muscle function is produced.

The computational simulation approach was a prospective candidate to establish the theoretical framework of how and when the counterintuitive HAM function is exerted. This is because this approach can clarify the causal relationship between the above two contributing factors while exerting a counterintuitive HAM function. When the muscle function was investigated, there are two main types of approaches. One is the experimental approach, and the other is the computational simulation approach. Electrical stimulation is often used to evaluate the muscle function in an experimental approach [16, 19, 24]. This approach is believed to be a powerful method for evaluating muscle function. However, there is a large limitation in which the correct evaluation of the muscle function with electrical stimulation is very difficult when the number of experimental conditions is large. This is because previous studies have shown that repeated contractions with electrical stimulation can cause a decrease in the produced muscle forces [25, 26]. Given that all conditions must be confirmed to achieve a comprehensive understanding, the results of those studies indicate that it seems to be impossible to confirm all the conditions. On the other hand, computational approaches have the potential to confirm all conditions without the effect of decreasing the produced muscle forces by repeated muscle contraction. Biomechanists believe that the advantage of computational simulations is that it demonstrates a causal relationship [27–29]. For this reason, computational simulation approaches have often been used in a wide range of fields, such as sports and rehabilitation.

The purpose of this study is to identify the situations under which HAM can act as knee extensors by using a computational simulation approach. We developed the following hypotheses for this investigation. 1) HAM can act as knee extensors regardless of the foot contact conditions. 2) The HAM function changes depending on the posture. Finally, the situation where the foot contacts the ground facilitates a counterintuitive HAM function. We tested these hypotheses by performing a musculoskeletal modeling simulation that takes into account the posture dependent moment arm ratio, intersegmental dynamics, and the contact conditions.

2. Materials And Methods

2.1. Model implementation

The Gait2392 model is a musculoskeletal model from OpenSim [30] and it was modified to conform to our computational simulation study. The Gait2392 model was defined in a three-dimensional space and it has 23 degrees of freedom and 92 muscles. We aimed to simplify this by restricting the model motion in the frontal and transverse planes. Therefore, the total number of degrees of freedom was 10; there were two translational factors (the point of the pelvis fore-aft and the vertical direction) and eight rotational factors (pelvis tilt, trunk bending, hip flexion, knee flexion, and ankle dorsal flexion). The biceps femoris long head was chosen as the delegation of the HAM.

2.2. Simulation

As stated earlier, the purpose of this study was to identify the situations under which HAM can act as knee extensors. In order to achieve this purpose, the simulation in this study was designed to quantify the HAM function on the knee joint for the two main contributing factors: the effect of changing the posture and the effect of the foot contact condition.

To evaluate the changing HAM function on the knee joint, this depends on the posture. The posture was determined by combining the right hip flexion angle that ranged from 90° to -30° and the right knee flexion angle, which ranged from 90° to -10° . This setting can cover a wide range of the knee and hip angles during movement such as walking [31], running [32], and vertical jumping [33]. In order for the simulation's setting to be simpler, we assumed that all the joint angles, except for the right hip and knee joint angles, were set to 0° .

To examine the effect of the contact condition on determining the HAM function, the simulations were executed under two conditions: non-contact with the ground (nCG) conditions and contact with the ground (CG) conditions. The simulation under the nCG condition was executed without the effects of the ground reaction force. In other words, all segments were able to move freely. In contrast, under the CG condition, the point constraint [34] was applied at the point of the right ankle joint. The point constraint does not allow the ankle joint to translate in any direction (i.e., fore-aft and vertical), although it allows the shank segment to rotate. The simulation under the CG condition was executed while considering the effect of the ground reaction force that is induced by HAM. The biggest difference between the two conditions is whether there is an effect of the ground reaction force that is induced by HAM. The constraint force was determined by using a technique that was previously reported [35].

The induced acceleration analysis [21, 22, 36] was applied to determine the contribution of HAM to the knee angular acceleration. In the simulation, we quantified the HAM-induced knee acceleration when a 1 N HAM force and the corresponding ground reaction force were applied to the model. These accelerations represent the capacity of the HAM per unit force. All calculations were performed by using OpenSim version 3.3 [30].

Three evaluation terms were used in this study to explain the results of our simulation. The first one is a “moment arm ratio”. The moment arm ratio was calculated by dividing the hip extension moment arm of the HAM by the knee flexion moment arm. If the moment arm ratio of HAM was larger than 1.0, this means that the effect of the hip extension that is induced by HAM is larger than the effect of the knee flexion, and vice versa. The second one is “knee angular acceleration induced by HAM”. A positive value indicates that the knee is extended, and vice versa. When the knee angular acceleration that is induced by HAM is positive, this means that the hamstring acts as the knee extensor. The third is “the range of the hip joint that HAM was able to act as a knee extensor ($RANGE_{HAM}$)”. $RANGE_{HAM}$ was defined as the value of the maximum hip flexion angle that HAM was able to act as a knee extensor minus its minimum. This evaluation term was used to quantify the impact of the contact conditions while determining the HAM function on the knee joint. If $RANGE_{HAM}$ is expanded or contracted, this implies that the contact condition has a positive or negative effect to exert a counterintuitive HAM function. $RANGE_{HAM}$ was quantified with knee flexion angles of 0 °, 20 °, 40 °, 60 °, and 80 °.

3. Results

The moment arm of HAM changed according to the displacement of the hip and knee angles [37, 38]. In other words, the moment arm ratio of HAM was determined by the hip and knee angles. Figure 1 shows the alternation of the moment arm ratio, which depends on the posture. The moment arm ratio of HAM varied from 0.8 to 3.9 depending on the posture. The moment arm ratio was lower than 1.0, which ranged from -30° to -24° for the hip flexion angle and 9° to 74° for the knee flexion angle. This means that in almost all cases, the effect of the hip extension that is induced by HAM is larger than the effect of the knee flexion that is induced by it.

The HAM can act as knee extensors under both conditions. However, when comparing the nCG condition to the CG condition, this indicates that the HAM function changed from the nCG condition to the CG condition. Figure 2(a) shows the alternation of the knee angular acceleration that is induced by HAM depending on the postures under the nCG condition. The knee angular acceleration induced by HAM varied from -11.7 to 10.1 deg/s² depending on the postures. Figure 2(b) presents the alternation of the knee angular acceleration that is induced by HAM depending on the postures under the CG condition. The knee angular acceleration that is induced by HAM varied from -6.6 to 14.4 deg/s² depending on the postures. Figure 3 shows the alternation of $RANGE_{HAM}$ from the nCG condition to the CG condition. $RANGE_{HAM}$ was expanded from the nCG condition to the CG condition in all individual knee flexion situations.

4. Discussion And Conclusions

The purpose of this study was to identify the situations under which HAM can act as knee extensors. To achieve this purpose, a musculoskeletal model-based computational simulation was designed to quantify the HAM function on the knee joint for the two main contributing factors: the effect of changing

the posture and the effect of the foot contact condition. This study revealed three main findings. 1) HAM can act as knee extensors that have contact with the ground (CG) condition but also non-contact with the ground (nCG) condition. 2) The HAM function changes depending on the posture. 3) Finally, the range of the hip joint that HAM can act as knee extensors ($RANGE_{HAM}$) was expanded to the CG condition from the nCG condition.

The first point to be discussed is the posture dependent HAM function. As mentioned earlier, posture is an important contributing factor. This is because the moment arm ratio and the intersegmental dynamics change depending on the posture. Many researchers have claimed that the biarticular muscle moment arm ratio of the proximal joint to the distal joint is the largest contributor to the counterintuitive function [9, 17, 19, 21]. In addition, some previous studies demonstrated that changing the muscle function was caused by the posture-induced changes in the effect of the intersegmental dynamics [14, 15, 18, 22]. Despite the situation described above, to the best of our best knowledge, a comprehensive study currently does not exist in terms of how the HAM function changes depending on the posture. This is the first study to show in detail the change in the HAM function on the knee joint depending on the posture.

The next discussion deals with the interaction between the moment arm ratio and the posture-dependent intersegment dynamics. Some researchers believe that the moment arm ratio has the largest impact on the counterintuitive biarticular muscle function [9, 17, 19, 21]. However, the results of the present study denied this notion. A typical example is shown in Fig. 4. Figure 4 indicates that the two different postures have the same moment arm ratio. Even though both postures have the same moment arm, the HAM function is different. This is evidence that the HAM function is determined by the interaction between the moment arm ratio and the intersegmental dynamics. We can conclude that the counterintuitive HAM function arose from the interaction between the moment arm ratio and the intersegmental dynamics, and that the interaction between these factors dynamically changes depending on the posture.

Thirdly, the effect of the foot contact conditions is discussed. In the present study, we confirmed that $RANGE_{HAM}$ was expanded to the CG condition from the nCG condition (Fig. 3). This finding indicates that whether the foot is in contact with the ground has a large impact on determining the HAM function. Previous studies have reported that the ground reaction force has a large effect in terms of determining the muscle function during movement [15, 17, 23]. Frigo et al. [15] investigated the alternation of the HAM function under different CG conditions by using a computational simulation approach. As a result, they clearly showed that the effect of the knee flexion that is induced by HAM is dramatically reduced while in contact with the ground conditions in comparison to the nCG condition. These results are consistent with our results. When considering these observations, we concluded that the exertion of the counterintuitive function of HAM is facilitated by the foot contacts on the ground. This finding suggests that the effect of the ground reaction force must be considered when investigating the muscle function.

We discussed the clinical implications of our findings. This study identified a situation in which HAM was able to act as the knee extensor. Previous studies have reported that the capacity to generate knee extension is one of the most important factors in predicting movement performance, such as gait velocity

[1–3]. In addition, it is well known that weakness of the quadriceps muscle causes abnormal knee joint movement during walking, especially in the stance phase of walking [4, 5]. Hence, in the rehabilitation region, therapists often try to improve this matter by enhancing the patients' quadriceps muscle. However, it is impossible for some patients, such as stroke patients with severe motor paralysis on the quadriceps muscles and patients who have undergone partial or total quadriceps resection to enhance the strength of the quadriceps muscle [6–8]. Figure 5 shows the knee angular acceleration that is induced by HAM under the CG condition with the hip and knee joint angles during the stance phase of walking, which was divided from Winter's data [31]. As demonstrated, the knee angular extension acceleration was exerted by HAM in all stance phases of walking. This indicates that HAM can act as knee extensors during the stance phase of walking. Therefore, our findings suggest that HAM can be used as compensatory movement strategy for patients with a reduced capacity to generate knee extension if the patients have enough HAM strength. We believe that our findings are meaningful in the biomechanics region and the rehabilitation region.

This study successfully provided a theoretical framework for how and when the counterintuitive HAM function is produced. Indeed, the results of the present study can explain the wide range of findings in previous studies [11, 12, 14, 15, 17–20]. However, there are some findings from the present study that we were not able to explain well. Thelen et al. investigated the HAM function during the terminal swing and loading response while walking by using electrical stimulation. As a result, Thelen et al. identified that HAM acted as the knee flexor during both phases [16]. According to the results of the present study, HAM should act as the knee extensor during the loading response while walking. There is a potential explanation why this gap occurred. We ignored the HAM function in the frontal and transverse planes, even though it has a three-dimensional moment arm [39]. The muscle action in the frontal and transverse plane has been demonstrated to contribute to the motion in the sagittal plane [40]. Additional studies are necessary to obtain a better understanding of this matter. However, it was determined that an appreciation of the mapping between the interpretations that are drawn from simple and complex models is needed to advance the understanding of movement mechanics [41]. Therefore, we believe our study provides useful information about determining the HAM function because we can clearly show the relationship between the main contributing factors while exerting the counterintuitive HAM function in the sagittal plane with a simple model.

In the present study, we investigated the independent action of HAM on the knee joint. This study did not consider the co-contraction effect of HAM and the quadriceps. Some studies have suggested that the co-contraction effect of HAM and quadriceps muscles is necessary to determine the HAM function [9, 10, 42]. However, the present study revealed that HAM can act as knee extensors without co-contraction. Frigo et al. investigated the co-contraction effect of HAM and the quadriceps muscle and they showed that it enhances the hip extensor effect of HAM and it reduces the knee flexor effect of HAM [15]. Unfortunately, only a few studies have investigated how much impact the co-contraction of HAM and the quadriceps muscles has in determining the HAM function. Therefore, further studies are necessary to identify the co-contraction between HAM and other muscles.

In conclusion, we have demonstrated that HAM can act as knee extensors. Our findings suggest that HAM might compensate for the capacity to generate knee extension during movement as knee extensors. In addition, our findings contribute to establishing the theoretical framework of how and when the counterintuitive function of HAM is exerted.

Declarations

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Conflict of interest

The authors declare we have no conflicts of interest.

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Authors' contributions

All authors wrote and edited the manuscript. Y.K conceived and designed the research. T.W and T.I created the model, analyzed results. T.T and M.K supervised the research.

Ethics approval

This study was a simulation study; thus, informed consent was not required.

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Figures

Figure 1

Moment arm ratio of the biarticular hamstring muscles (HAM). The colors for this figure represent the magnitude of the moment arm ratio of HAM. The black solid line indicates the postures that the moment arm ratio of HAM was 1.0. If the moment arm ratio is larger than 1.0, this means that the effect of the hip extension that is induced by HAM is larger than the effect of the knee flexion. Therefore, the black solid line implies the boundary to change the predominance of the effect of the hip extension that is induced by HAM over the effect of the knee flexion.

Figure 2

Knee angular acceleration that is induced by the biarticular hamstring muscles (HAM) for the conditions of (a) non-contact with the ground (nCG) and (b) contact with the ground (CG). The shift to the color white indicates that the knee extension angular acceleration is induced by HAM. Conversely, when the color is shifted to black, this indicates that the knee flexion angular acceleration is induced by HAM. The black solid line means that the postures for the knee angular acceleration is zero. If the knee angular acceleration is larger than 0, this means that HAM generated knee extension angular acceleration. Therefore, a black solid line implies the boundary to change the HAM function to the knee extensor from the knee flexor.

Figure 3

Alternating the range of the hip joint that HAM can act as knee extensors ($RANGE_{HAM}$) from the condition for non-contact with the ground (nCG) to the condition where there is contact with the ground (CG). (a) Knee angular acceleration is induced by the biarticular hamstring muscle (HAM) under the nCG condition. (b) Knee angular acceleration is induced by HAM under the CG condition. Black arrow lines in (a) and (b) indicate $RANGE_{HAM}$ for individual knee flexion angles. (c) A comparison of $RANGE_{HAM}$ for the nCG and CG conditions.

Figure 4

Example of the interaction between the moment arm ratio and the intersegmental dynamic. (a) Knee angular acceleration that is induced by the biarticular hamstring muscle (HAM) for the condition of non-contact with the ground (nCG). (b) Moment arm ratio of HAM. (c) The posture for situation 1. (d) The posture for situation 2. The HAM function was different for the two different postures even though both postures have the same moment arm ratio.

Figure 5

Knee angular acceleration that is induced by the biarticular hamstring muscle (HAM) for the condition that is in contact with the ground (CG). The black arrow line shows the knee and hip joint angles during the stance phase of walking, which was divided from Winter's data (Winter, 2009).