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The role of the biarticular hamstrings and gastrocnemius muscles in closed chain lower limb extension

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HIGHLIGHTS

- A muscle's role is only partially described by its effect on the joint it spans.
- Analysing a muscle's effect on body segments can provide greater insight.
- The biarticular hamstrings extend the pelvis and femur and flex the tibia.
- Gastrocnemius extends the tibia and foot and flexes the femur.
- Quadriceps involvement in lower limb extension is facilitated by these structures.

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ABSTRACT

The role of the biarticular muscles is a topic that has received considerable attention however their function is not well understood. In this paper, we argue that an analysis that is based upon considering the effect of the biarticular muscles on the segments that they span (rather than their effect on joint rotations) can be illuminating. We demonstrate that this understanding is predicated on a consideration of the relative sizes of the moment arms of a biarticular muscle about the two joints that it crosses. The weight of the previous literature suggests that the moment arms of both the biarticular hamstrings and gastrocnemius are smaller at the knee than at the hip or ankle, (respectively). This in turn leads to the conclusion that both biarticular hamstrings and gastrocnemius are extensors of the lower limb. We show that the existence of these biarticular structures lends a degree of flexibility to the motor control strategies available for lower limb extension. In particular, the role of the gastrocnemius and biarticular hamstrings in permitting a large involvement of the quadriceps musculature in closed chain lower limb extension may be more important than is typically portrayed. Finally, the analysis presented in this paper demonstrates the importance of considering the effects of muscles on the body as a whole, not just on the joints they span.

1. Introduction

The study of muscular functional anatomy is concerned with understanding the role of individual muscle elements (both individually and in concert with other muscle elements) in creating and resisting movement of the musculoskeletal system. Typically, the musculoskeletal system is conceived as a system of rigid segments that are connected by joints that act as hinges between the segments. The functional anatomy of a muscle element is then described in terms of the inter-segmental joint moments that the muscle tends to create about the "joint hinge". The bulk of the biomechanics literature has adopted this "joint-based" conception of musculoskeletal function, and biomechanical analyses of motion are described and solved based upon considerations of joint moments and muscle moments.

Recently we have argued (Cleather et al., 2011a,b,2013; Cleather and Bull, 2011, 2012) that it may be more appropriate to utilize a "segment-based" approach to the description and analysis of musculoskeletal function. A segment-based biomechanical analysis is based upon considering the rotation effect that muscle elements, ligaments and joint reaction forces exert upon the segments they span. This approach has the potential to provide an insight as to musculoskeletal function which is in part

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precluded by joint-based approaches. A key reason for this is that joint-based approaches often do not explicitly include all of the forces that act upon the segments. For instance, it is common that the rotational effects of the joint reaction forces are not explicitly described—instead their effects are implicitly captured by the assumption of the "joint hinge". Thus, in a joint-based approach, some of the detail as to how the forces created by the muscles create movement is lost. This limitation may be particularly important when considering some of the more complex architecture of the musculoskeletal system. For example, the reaction force between the patella and femur has a strong rotation effect on the femur (Cleather et al., 2014); however, this is not included in a standard joint-based approach.

The role of the biarticular muscles of the lower limb is not well understood, and there have been a number of theories advanced to explain their purpose (Van Ingen Schenau and Cavanagh, 1990; Bobbert and van Ingen Schenau, 1988; Lichtwark and Wilson, 2006; Baratta et al., 1988; Bobbert et al., 1986a,b) (these are described later in more detail). However, as we will show in this article, the use of a segment-based approach to analyze the function of the biarticular muscles can provide further detail as to their role. In particular, in this paper we will use a segment-based approach to analyze the role of the biarticular hamstrings and gastrocnemius during closed kinetic chain lower limb extension (CKE). This choice has been made due to the major role that these biarticular muscles are thought to play in these activities (Van Soest et al., 1993; Jacobs et al., 1996).

2. The joint contact forces caused by a biarticular muscle rotate the intermediate segment spanned by the muscle

In a remarkably insightful paper (Zatsiorsky and Latash, 1993) that appears to have largely passed unnoticed by the biomechanics community (with zero citations as measured by standard databases 20 years after publication), Zatsiorsky and Latash described the mechanism by which biarticular muscles create rotations of the segments which they span. Their work is a great illustration of the benefits of employing a segment-based analysis. In particular, the effect of a biarticular muscle can only be properly characterized by considering the joint reaction forces that it creates. As the simplified segment-based analysis in Fig. 1 shows, a biarticular muscle creates a rotation of all three segments it spans. The proximal and distal segments are rotated by the couples created by the line of action of the muscle force in combination with the joint reaction force that it creates. The intermediate segment is rotated solely by the joint reaction forces created by the biarticular muscle.

Based upon a consideration of Fig. 1, it is apparent that the direction of rotation of the intermediate segment spanned by a biarticular muscle is dependent on the relative size of its moment arms about each joint that it spans. For instance in Fig. 1, the moment arm (d_2) of the biarticular muscle about the distal joint is greater than the moment arm (d_1) about the proximal joint. The moment arm of the joint reaction forces on the intermediate segment ($d_3 = d_2 - d_1$, see Fig. 1 and Zatsiorsky and Latash (1993)) thus causes a counter-clockwise rotation of the segment.

In this paper, we will define an extension moment to be one that rotates a lower limb segment in a direction that is consistent with a lower limb extension. So for instance, in Fig. 1 a counter-clockwise rotation of the intermediate segment (the tibial segment) would be defined to be extension and a clockwise rotation to be flexion. In this figure the (illustrated) moment arm of the gastrocnemius is smaller at the superior joint (representing the knee) than at the inferior joint (ankle) which would suggest that the gastrocnemius creates an extension of the tibial segment.

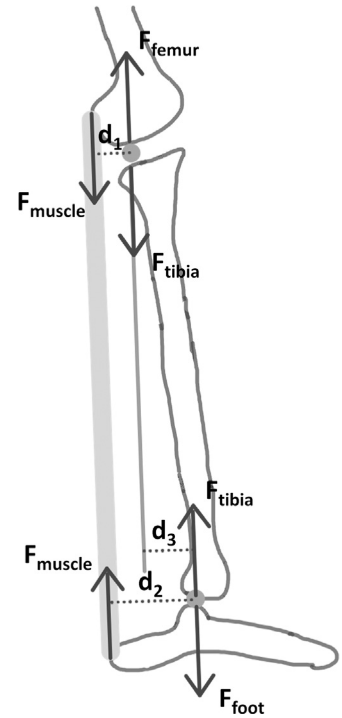

Fig. 1. Rotation of body segments by a biarticular muscle (Zatsiorsky and Latash, 1993) (in this case the action of gastrocnemius is illustrated). *Notes*: The thick, light grey line indicates the gastrocnemius muscle, and the grey circles indicate the centres of rotation of the joints. The black arrows indicate the forces created by tension in the muscle where F_{muscle} is the magnitude of the force directly exerted by the muscle, F_{femur} is the joint reaction force acting on the femur, F_{tibia} is the reaction force acting on the tibia, F_{foot} is the reaction force acting on the foot, and $F_{muscle} = F_{femur} = F_{tibia} = F_{foot}$. The dotted lines d_1 and d_2 indicate the moment arms of gastrocnemius about the knee and ankle joints, respectively. The moment arm of the couple created by the joint reaction forces acting on the tibia (d_3) can be seen to be equal to $d_2 - d_1$.

However, if the moment arm at the knee was greater than at the ankle then the gastrocnemius would create a flexion of the tibial segment. It is therefore clear that in order to understand the function of the biarticular muscles (and in particular their effect on the intermediate segments that they span) that it is necessary to compare the moment arms of the muscles at the joints they span. One aspect of this paper is therefore to review the previous literature that has quantified the moment arms of two important biarticular muscle groups of the lower limb (the biarticular hamstrings and gastrocnemius) in order to characterise their function in terms of their effects on the intermediate segments they span, and then in turn to propose a fundamental description as to the role of the biarticular muscles that is precluded by a joint-based approach.

3. The biarticular hamstrings and gastrocnemius are predominantly lower limb extensors

There is a large body of literature that has attempted to quantify the moment arms of the musculature of the lower limb. Interestingly, and probably reflecting the dominance of the joint-based paradigm, a minority of these have evaluated the moment arms of biarticular muscles at both joints that they cross. In addition, the measured moment arm is dependent upon the method used to quantify it (Maganaris et al., 2000; Maganaris, 2004; Fath et al., 2010). Thus to the casual reader of the literature it is not straightforward to ascertain the relative sizes of the biarticular hamstrings' moment arms at the hip and knee, or the