An Analytical Approach to Posture-Dependent Muscle Force and Muscle Activation Patterns

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Abstract— **Personalized training by taking into account individual anatomy to improve performance is a research frontier. In this paper, we first introduce an analytical method to study the pattern of changes in muscle forces as a function of posture. Our method is also able to analyze variation of maximal muscle force and muscle activation values (in various postures) as a result of posture-dependent changes in moment arms. This method also helps us evaluate the utility of person specific training. It also provides us with model based approximations for activation and muscle force patterns during different motions without a need for subject recordings, which enables athletes to have a better understanding of how each muscle contributes during each posture, in a fast and efficient way. Second, we analyze the results of this method for a simple squat move. Our results show that both maximal muscle force and muscle activation values have variable sensitivity to the moment arm values for different postures and muscles. It suggests that individually modified training plans could likely improve performance for some sets of movements.**

I. INTRODUCTION

Athletes often perform a variety of exercises to assist in enhancing their performance and optimizing their skill set for their sports. In addition, athletes can use some of the same exercises to enhance the rehabilitation process [1]. However, incorrect form can initiate severe damage to muscle tissues that cause impairment to motion and long-term injuries [2]. One of the most fundamental exercises performed by athletes is the squat [3]–[5]. The squat is a movement that can reveal the robustness and condition of the lower-limbs, such as leg alignment [6], efficiency of performance output [7], and functional deficits [8]. The squat is also used to evaluate the muscle activation in rehabilitative stroke patients [9]. We are also interested in the squat motion since it does not necessarily require complex physical models to analyze it.

Studying muscle activity patterns is essential in improving athletes' performances and prompting faster rehabilitation [10]. EMG analysis is the most commonly used technique to address this need [5], [10]. However, the process of gathering EMG records often presents disadvantages with being time-consuming, demanding expensive hardware usage, requiring expert participation that may not be readily available, and is not practical in some situations; e.g., studies involving children [11]. Moreover, the practical EMG systems are mostly limited to the surface muscles. Therefore, model based approaches are more attractive in cases with any of the above-mentioned limitations.

In addition, there is an increasing interest in taking individual variability into account to mitigate muscle damage as well as devising the best training strategy for each person [12], [13]. Scientists have turned to personalized (precision) medicine and health [14], [15] to understand the intricacies that play a role in muscle development per person. Personalized health for athletic training often investigates the connection between genetics and exercise response [16]–[18]. However, there is also value in exploring the dynamics between neuromechanics [19], [20] and exercise response [5]. It is also not clear if personalized training is actually necessary for a particular move and, even if it is, which muscles are more effected by the variations in biomechanical properties in individuals. In this paper, we investigate the necessity of exercise routines and training regimens that are tailored to the unique constraints and musculoskeletal structure of individual subjects rather than the population average.

The aforementioned issues of providing a feasible alternative to EMG analysis and attempting to apply personalized medicine to physical training in a practical way were addressed by devising a model-based approach and sensitivity analysis for the model parameters, respectively. In this study, we have introduced a method to analyze muscle forces and activation levels in different postures and investigate their behavior in response to variation in moment arm values. Here, we have analyzed the muscle activities in the squat motion (in a quasi-static case) during the rising up phase of the squat cycle; however, it needs to be noted that this method can be applied to any other motions. In our simulations, the primary objective was to maximize the endpoint force in the vertical direction (upward) and examine the contribution of each muscle as a function of posture. We have used linear optimization to find the muscle activation patterns for which the vertical force is maximal and performed Monte Carlo analysis to study the sensitivity of maximal muscle forces and muscle activation patterns in each posture to the moment arm values.

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II. Methods

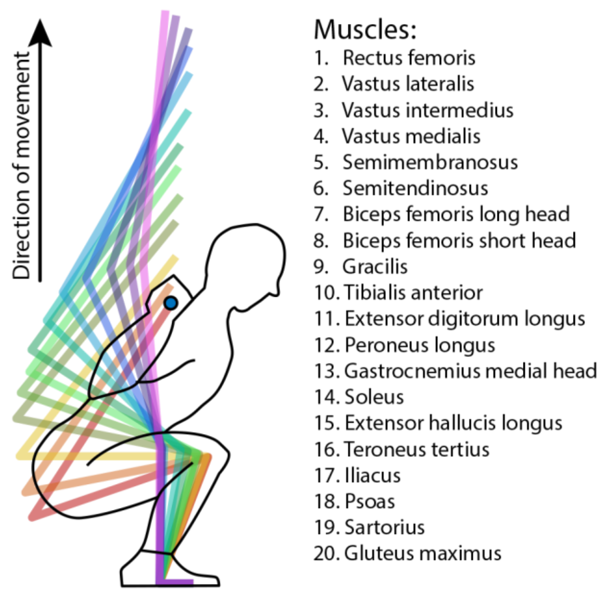

Fig. 1. Thirteen different postures used in the simulations (a). List of the muscles in the model (b).

A. Biomechanical model

In this study, we use a simplified three joint (ankle, knee, and hip) planar model of the human leg with 20 muscles. The complete list of these muscles is shown in Fig. 1. More information on each muscle (i.e., optimal lengths, peak forces, etc. are available at [21]). The tendon routing of the model we are using is illustrated in Fig. 1. In this model, we have assumed stiff tendon properties and fixed moment arm values as a function of joint angles.

Here, we are only considering the quasi-static case during each posture (and by so, we can avoid unnecessary complications that movement kinematics will cause). We have also disregarded weights of different leg parts since they are very small compared to the torso plus weights that the athlete will move during the squat move. In addition, our model is limited to the sagittal plane.

B. Monte Carlo analysis

To incorporate the differences between different subjects in terms of the moment arm values as well as finding the sensitivity of the results to these values, we performed a Monte Carlo analysis. We have randomly (uniform distribution) changed the moment arm values within ±25% of their original values.

C. Positions

Joint angles for 13 different postures were manually extracted from a video of a professional trainer performing the squat movement. These inputs were later fed to the MATLAB code. Only the movement from a full squat to an upright position was considered. The transition between these postures is illustrated in Fig. 1.

D. Kinetics equations and the linear optimization

The forward kinematic model (also known as the Geometric Model [19], G) of the three DOF model used in this study is defined on Eq. 1 [19].

$$G(\boldsymbol{\theta}) = \begin{pmatrix} x \\ y \\ \varphi \end{pmatrix} \tag{1}$$

where $\boldsymbol{\theta}$ is the vector of joint angles and x, y, and φ are the horizontal position, vertical position, and rotation of the endpoint, respectively. The equation for the corresponding wrench space (w) of this forward model is defined in Eq. 2:

$$w(\boldsymbol{\theta}) = \begin{pmatrix} f_x \\ f_y \\ \tau_\varphi \end{pmatrix} = H(\boldsymbol{\theta})\boldsymbol{\alpha} = J(\boldsymbol{\theta})^{-T} R(\boldsymbol{\theta}) F_0(\boldsymbol{\theta})\boldsymbol{\alpha} \tag{2}$$

where J is the Jacobian matrix, R is the moment arm matrix, F_0 is the diagonal maximal muscle force matrix and $\boldsymbol{\alpha}$ is the muscle activation vector. The effects of the length of muscles on their forces [19] were also applied during calculations of the maximal muscle force for each muscle in each posture. The goal of the linear optimization [19] exploited in this study is to find the muscle activation patterns for each posture that maximize the vertical force at the endpoint in the upward direction (positive in y axis) while limiting the horizontal forces (less than 10N) at the endpoint as well as keeping activation values between 0 and 1. The equations governing the linear optimization performed in this study are described in Eq. 3:

$$maximize\ \boldsymbol{c}^T \alpha\ s.t. A\boldsymbol{\alpha} \leq \boldsymbol{b} \tag{3}$$

where $\boldsymbol{c}$ is the cost function vector, here the second row of H matrix defined on Eq. 2, and A and $\boldsymbol{b}$ define the linear inequality constrains discussed earlier. In addition, muscle excursion is defined as the change in the length of a muscle (more accurately, musculotendon length) from its reference state. The vector of muscle excursions, $\delta\boldsymbol{s}$, was calculated using Eq. 4:

$$\delta\boldsymbol{s} = -R^T \delta\boldsymbol{q} \tag{4}$$

where $\delta\boldsymbol{q}$ is the joint angle displacement vector.

E. Force-length properties of muscles

The maximal muscle force that each muscle can produce is a function of muscle length and muscle velocity. We have applied peak force values for each muscle to their force-length curves to calculate the maximal muscle force during each posture. Moreover, since we are doing a quasi-static analysis, we did not apply force-velocity equations.

III. Results

One hundred Monte Carlo runs (with ± 20% change in the moment arm values) were performed for each posture. Linear optimization results showed us that optimal activation values were distributed very sparsely. I.e., 95% of activation values were either zero (not activated at all) or one (fully activated). These activation values were further multiplied to the maximal muscle force for each posture to produce the exerted muscle forces. Exerted muscle force values as a function of posture are illustrated on Fig. 2. In this figure, force values of each muscle in each posture were calculated by averaging over all Monte Carlo run results for that muscle and posture combination. We can see that there is a pattern in which muscles tend to exert higher forces centered around Posture 6. We also observe that for this specific task (maximizing the upward force), the force value for different stages of the movement has high variation for some muscles, while it is relatively more consistent (or even all zeros) for some other muscles.

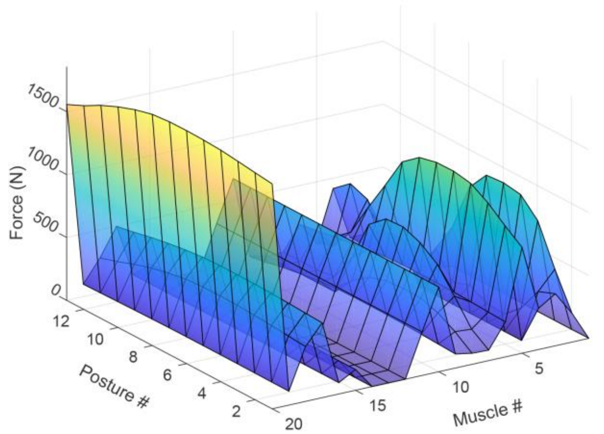

Fig. 2. Exerted muscle force values as a function of posture (averaged across all the Monte Carlo runs). See Fig. 1 for the list of the muscles.

Fig. 3 shows maximal muscle force values (for all the Monte Carlo runs) as a function of posture for six selected muscles (red) as well as the exerted muscle force values (blue), which are, as mentioned earlier, maximal muscle forces multiplied in their corresponding activation values. The parts in which red and blue lines overlap are blue depicted in purple. These plots illustrate the sensitivity of the results to the moment arm values in each posture.

IV. Discussion

In this paper, we have introduced an analytical method to study muscle activations and their sensitivity to moment arm values during different tasks. Using this method, we have provided the results on how muscle forces change in different postures during a sample task (maximizing upward force during a squat move). We have also studied the sensitivity of the output force for each muscle in different postures to the moment arm values.

Since our simplified biomechanical model does not use a feedback controller and excludes balance and weight factors, it does not reproduce some co-contractions seen in biological systems and muscles here are activated mainly to fulfill the optimization goal (maximizing the upward force). This explains the sparsity of the activations for muscles and the lack of activation for the muscles which do not contribute toward the goal.

Fig. 2 shows us that patterns in force value (as a function of posture) can be considerably different across muscles. Using this figure, we can find out how much force each muscle (on average across different moment arm values) will exert in every single posture. This will help athletes to find posture in which they can focus more on a specific muscle as well as helping individuals suffering from injuries to avoid or get support during the postures in which their injured muscles will be highly activated. Fig. 2 also shows that although there are variations in the force patterns across different muscles, most of the muscles have higher values around Posture 4 to 6. These findings are generally, even with the aforementioned simplifications of the model, in agreement with the subject based studies made by EMG recordings [5]. The reason for these peaks in the muscle force curves is that, in our model, most of the muscles are on their optimal length around halfway through the squat move and therefore their force-length curve values are maximal in that position.

In Fig. 3, we have selected four different muscles as a subset to represent the most important types of muscle force and muscle activation patterns we observed during the simulation. Plots in this figure show that maximal muscle force (red) in some muscles (e.g., vastus lateralis, semimembranosus, biceps femoris short head) is highly sensitive to the moment arm values while it is not in some others (e.g., gluteus maximus). It also shows that even in the muscles with high sensitivity to the moment arm values, this sensitivity can change in different postures. These two findings are important since they affirm that our simulation results can help athletes, coaches, and individuals in planning their exercises while being able to evaluate the need to make individualized adjustments. I.e. these simulation results enable physically active individuals to evaluate whether they would be safe from injuries with a general exercise plan (if the sensitivity in muscle/posture was low) or they need individualized adjustments (if the sensitivity was high). These adjustments can be in terms of the postures they should put more focus on (trying to increase the amount of the exerted force or the time duration spent during that posture) or the postures they need to avoid (or get help with) during their practices.

Fig. 3 also shows us that even in cases where the maximal force value is not sensitive to moment arm values, the actual

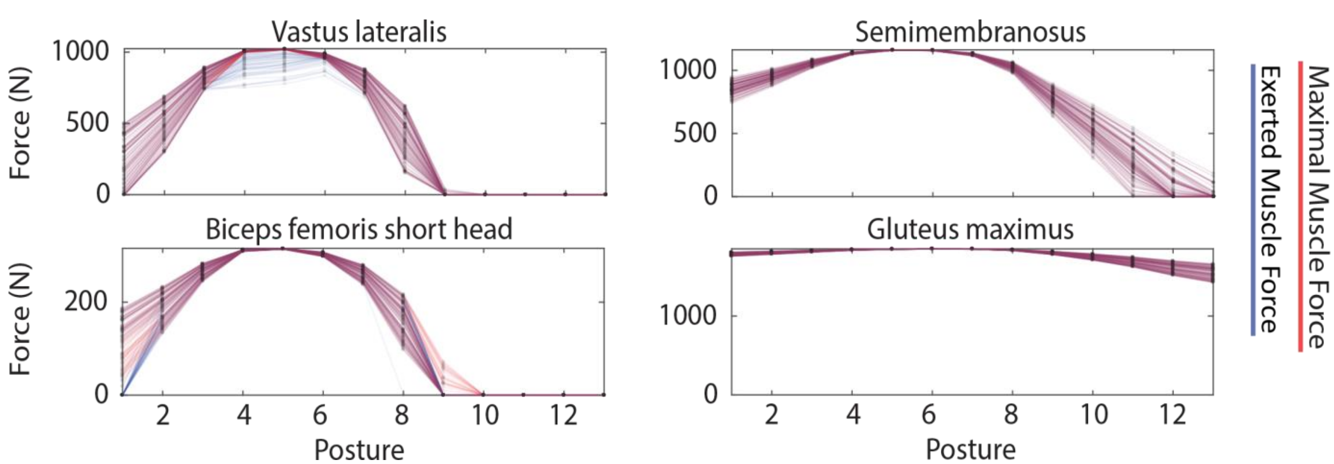

Fig. 3. Four selected muscles to represent the most important types of muscle force and muscle activity patterns we observed during the simulations.

exerted force (maximal force × activation value) can be (e.g., vastus lateralis, biceps femoris short head). This means that even if the maximal force is not sensitive to the moment arm values, personalized planning might be needed in performing some tasks due to the sensitivity in the activation values. Moreover, Fig. 3 shows that, just like the sensitivity of the maximal force value, the sensitivity of the activation values does not follow a simple pattern and can change based on the muscle and posture. Therefore, for each training, a biomechanical analysis similar to what is provided here is needed to evaluate the need of personal training in each posture.

Finally, although the general pattern of our results is consistent with experimental studies, there are some differences (e.g., sparsity of the activation values and some muscles being completely inactive). We believe that factors such as imposed constraints of the task, simplicity of the model, quasi-static assumption for the task, and lack of a feedback controller to perform the task are main contributors to these mismatches. We believe that, although our model performed well even with the simplifications made here, adding more physical and kinematical details can increase the precision of its results even further.

In terms of the potential future work, we believe that one interesting avenue to pursue is to add more details to the model, especially physics of the movement (E.g., inertias, accelerations, etc.), to have it more in line with the real-world kinematics. In addition, comparing these findings with more comprehensive clinical studies, especially intramuscular recordings from non-surface muscles, would be particularly helpful in assessing the accuracy of the proposed methodology.

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