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INFLUENCE OF HIP MUSCLE ACTIVITY ON FEMORAL NECK BONE MECHANICS

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SUMMARY

Physical exercise is widely recommended to promote bone health and mitigate the detrimental effect of osteoporosis. However, contrasting bone responses to different physical exercise interventions have been shown. The current study hypothesized that different muscle groups have the potential to load the femoral neck to varying levels. A validated finite-element (FE) model of the femur was used in conjunction with a validated musculoskeletal model from the same donor. Maximal isometric contractions of the hip-spanning muscle groups were simulated for a set of static postures spanning physiological ranges of motion. Strain energy and peak tensile strain in the femoral neck were calculated to evaluate the influence of hip muscle activity on femoral neck bone mechanics. The hip extensors induced the highest levels of peak strain and strain energy due to their size and location relative to the hip joint. Our results suggest that hip extensor muscle activity may be used in exercise interventions designed to maximally stimulate bone growth in the femoral neck.

INTRODUCTION

Osteoporosis, falls and related fragility fractures are significant public health problems affecting an increasing number of individuals. Evidence suggests that increased bone loading stimulates bone growth resulting in increased bone strength. Physical exercise is widely recommended to increase bone loading and mitigate the detrimental effect of osteoporosis [1]. However, several different exercise treatments have been studied showing a highly variable bone response in the femoral neck region, making it difficult to identify the optimal exercise treatment for femoral neck bone health. The current study hypothesized that the different hip-spanning muscle groups have the potential to load the femoral neck to varying levels, thereby causing varying levels of stimuli for bone growth. Differences in musculoskeletal geometry, muscle physiological cross-sectional area (PCSA), and joint configuration will contribute to different patterns of femoral neck loading.

An effective way to explore the contribution of each muscle group to femoral neck mechanics is via computational modelling. Musculoskeletal models have been used to calculate subject-specific musculoskeletal loads. Finite-element (FE) bone models based on computed tomography (CT) scans also have been used to obtain subject-specific estimates of femoral neck mechanics. These two modelling approaches can therefore be amalgamated to investigate the differing effects of alternative physical activities on femoral neck mechanics. The aim of this study was to quantify femoral neck loading for different configurations of the hip and knee joints during maximal isometric contractions of isolated hip-spanning muscle groups.

METHODS

A validated FE model of a human cadaveric femur was created and used to calculate femoral neck mechanics under several loading regimes. The loading regimes represented muscle and joint-reaction forces on the femur at different configurations of the hip and knee joints and were calculated using a subject-specific musculoskeletal model based on the donor of the femur.

Medical image and dissection data of a donor (female, 81 yr, 63 kg, 167 cm) available from a public data repository [2] were used to create a lower-limb musculoskeletal model and a corresponding FE model of the femur. The FE model of the femur was created from computed-tomography images following a well-established procedure [3]. It was then validated using experimental loads and measured surface strains reported for the same femur [2].

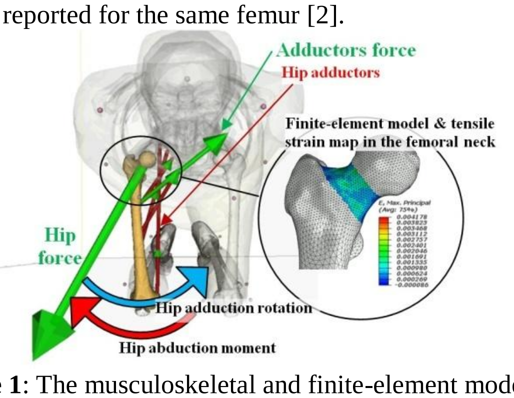

Figure 1: The musculoskeletal and finite-element models.

The musculoskeletal model (Figure 1) was generated from a full-body dissection and was carefully validated against experimental data as part of another study [4]. The peak isometric force of each muscle was calculated by multiplying the PCSA of the muscle by the tetanic muscle stress (TMS). The PCSA was measured in an earlier study [4]. Since there is a large variation in published values of TMS, all analyses were repeated using the minimum (0.35MPa) and maximum (1.37MPa) values reported in the literature [6]. The hip-spanning muscles were grouped by function (Table 1). The range of motion for each joint was defined within physiological limits (Table 2). Fifteen intermediate, uniformly-distributed angles were defined for each joint within its range of motion. Muscle forces were calculated by fully activating the relevant (Table 2) hip-spanning muscle group with the joint angle fixed (isometric contraction).The hip joint-reaction force was calculated by solving for static equilibrium of the femur neglecting the inertial forces. The hip joint-reaction force and muscle forces formed a loading regime to be applied to the FE model. The distal end of the femur was constrained in each simulation. The total number of loading regimes was 180 (6 muscle groups × 15 joint angles × 2 TMSs).

Table 1: The muscles grouped according to function

Hip abductors	**Hip adductors**	**Hip flexors**
Gluteus medius Gluteus minimus Tens. fascia lat.	Adductor brevis Adductor longus Adductor magnus Gracilis	Ileo-psoas Rectus femoris Sartorius
Hip extensors	**Knee extensors**	**Knee flexors**
Bicep femoris lh Gluteus maximus Semimembranosus Semitendinosus	Rectus femoris Vastus Intermedius Vastus lateralis Vastus medialis	Bicep femoris lh Biceps femoris sh Semimembranosus Semitendinosus

Table 2: Studied joint angles and range of motion (ROM).

Joint rotation (+)	**Activated muscle group**	**ROM (deg)**
Hip abduction	Hip abductors	From 0 to 40
Hip abduction	Hip adductors	From 40 to 0
Hip flexion	Hip flexors	From -20 to 30
Hip flexion	Hip extensors	From 30 to -20
Knee flexion	Knee extensors	From 90 to 0
Knee flexion	Knee flexors	From 0 to 90

All analyses were performed in ABAQUS© (Dassault Systèmes Inc., USA). Strain energy stored in the femoral neck (a global parameter) and peak tensile strain (a local parameter) were calculated and compared.

To evaluate the effect of muscle path geometry, strain energy (quadratically related to the magnitude of force) was normalised by muscle PCSA squared, while tensile strain (linearly related to the magnitude of force) was normalised by muscle PCSA thereby removing the effect of size.

RESULTS AND DISCUSSION

For the FE model validation, there was good agreement between the calculated and measured surface strains (R^2 = 0.95, RMS error = 12.5%).

When the hip muscles were maximally activated, the minimum reported TMS value of 0.35 MPa resulted in a mean (averaged over 90 loading regimes) femoral neck strain energy of 20 Jx10^{-3} and a mean peak tensile strain of 1287 με. By comparison, the maximum reported TMS value of 1.37 MPa resulted in mean femoral neck strain energy of 233 Jx10^{-3} and a mean peak tensile strain of 4504 με. These large changes in mean strain energy and mean peak tensile strain suggests that (a) accurate estimation of muscle strengths is critical in patient-specific calculations of bone strain; and (b) muscle strength training may be an effective treatment for maintaining bone strength in the femoral neck. Assuming a TMS of 0.35 MPa, the hip extensors induced the highest mean strain energy (70 Jx10^{-3}) and mean tensile strain (3238 με), whereas the knee extensors induced the lowest mean strain energy (0.2 Jx10^{-3}) and mean tensile strain (187 με) (Figures 2 and 3).

The difference between the highest and lowest values as a percentage of the mean was 155% for strain energy and 105% for peak strain. The magnitudes of these parameters were decreased by approximately one-half (74% and 48%, respectively) when strain energy and peak strain were normalised. These results suggest that variations in peak isometric muscle force (which is linearly related to PCSA) contribute significantly to the large range in femoral neck loads calculated for the various hip muscle groups (Figures 2 and 3). The fact that differences in femoral neck loading were not completed eliminated by the normalisation method adopted in this study also indicates that muscle path geometry contributes significantly to femoral neck loading.

Strain energy and peak tensile strain variations during hip extensor contractions never exceeded 5.9% of their mean value over the 15 different joint angles.

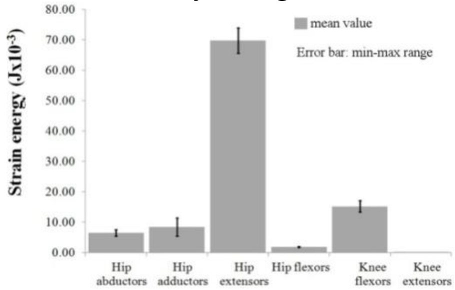

Figure 2: Strain energy calculated in the femoral neck.

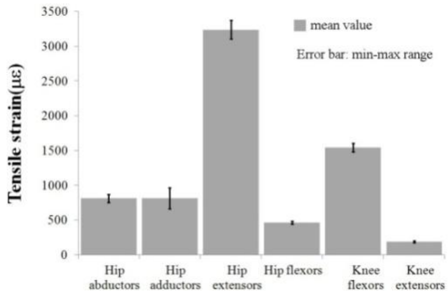

Figure 3: Peak tensile strain calculated in the femoral neck.

CONCLUSIONS

The results showed that contractions of the hip extensor muscles are most effective in generating high femoral neck loads. Exercise treatments involving the hip extensor muscles appear optimal for effectively loading the femoral neck irrespective of the hip extension angle at which the exercise is performed. These results can be used in the design of exercise interventions designed to stimulate bone growth in the femoral neck.

ACKNOWLEDGEMENTS

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