Optimal or Antagonistic? Muscle force solutions in the lower limb.

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INTRODUCTION

The musculature of the lower limb is redundant in nature. When calculating the muscle forces using a mathematical musculo-skeletal model it is necessary to select a criterion for muscle force distribution. For example, optimization may be used to minimize the sum of muscle forces, or minimize the maximum muscle stress. One method of validating these internal force distribution calculations is to use internal force measurements made with instrumented implants [2,4].

The current paper provides evidence of the appropriateness of various muscle force distribution protocols in a musculoskeletal model of the lower limb [1]. Calculated hip joint contact forces (HJCF) are directly compared with simultaneously acquired in vivo loads.

METHODS

HJCF were measured in-vivo using instrumented femoral prostheses [3,4]. These measures provided the 'gold standard' for comparison with calculated forces. HJCF were calculated using a lower limb musculoskeletal model [1]. This model described the 3D anatomy of the lower limb including hip, knee and ankle. Inverse dynamic methods were applied to motion and force plate data. Two subjects took part in various tasks and results are presented for one male (170.4cm, 92.3kg, 58 years, 36 months post-op., right side THR). The calculations of HJCF during one typical walking trial are examined here.

The muscle force distribution problem was solved using four different optimization criteria (C):
C1. Minimization of the sum of muscle forces
C2. Minimization of the sum of the square of muscle forces
C3. Minimization of the sum of the cube of muscle forces
C4. Minimization of the maximum muscle stress

RESULTS AND DISCUSSION

Figure 1 provides a comparison of HJCF calculated using the musculoskeletal model with forces simultaneously measured, using the instrumented implants. The forces are illustrated in an axis set attached to the femur with neutral orientation based on radiographs incorporating femoral neck anteversion.

Direct comparison of the calculated and measured forces illustrates a number of points:

- It was possible to provide a muscle force solution that satisfied equilibrium, but that consistently underestimated HJCF (C1) suggesting that the physiological solution does not use minimization of joint force as a criterion.
- Although solutions exist that 'optimize' criteria associated with muscle force, none of those used provided consistent agreement with the measured forces, e.g. C4 overestimated at some points in the gait cycle and underestimated at others.
- All criteria underestimated the HJCF during late stance suggesting that the body uses antagonism to provide extra stabilization at the joints during this phase of walking, or that the hip joint was hyper extended producing force in the ilio-femoral ligament that was not accounted for in the model.

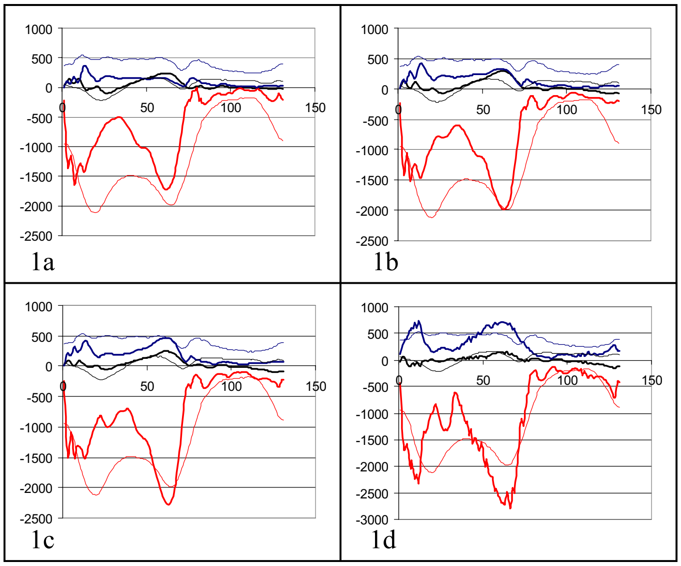

Figure 1 Calculated (thick lines) and measured (thin lines) HJCF (Newtons force vs. samples at 120Hz). Black – X (anterior-posterior); Red – Y (femoral long axis), Blue – Z (medio-lateral). 1a) C1; 1b) C2; 1c) C3; 1d) C4.

CONCLUSIONS

Although the authors recognize the significant contribution of the musculoskeletal model in determining HJCF, the results suggest that the physiological solution to the redundancy problem is not to operate an optimal criterion aligned with any of those investigated.

The results also suggested that the body uses a degree of antagonism above that required to provide stability at certain instances during the walking cycle or, as at the knee, moments may be transmitted by forces in ligaments.

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