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Strain energy in the femoral neck during exercise

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ABSTRACT

Physical activity is recommended to mitigate the incidence of hip osteoporotic fractures by improving femoral neck strength. However, results from clinical studies are highly variable and unclear about the effects of physical activity on femoral neck strength. We ranked physical activities recommended for promoting bone health based on calculations of strain energy in the femoral neck. According to adaptive bone-remodeling theory, bone formation occurs when the strain energy (S) exceeds its homeostatic value by 75%. The potential effectiveness of activity type was assessed by normalizing strain energy by the applied external load. Tensile strain provided an indication of bone fracture. External force and joint motion data for 15 low- and high-load weight-bearing and resistance-based activities were used. High-load activities included weight-bearing activities generating a ground force above 1 body-weight and maximal resistance exercises about the hip and the knee. Calculations of femoral loads were based on musculoskeletal and finite-element models. Eight of the fifteen activities were likely to trigger bone formation, with isokinetic hip extension ($\Delta S = 722\%$), one-legged long jump ($\Delta S = 572\%$), and isokinetic knee flexion ($\Delta S = 418\%$) inducing the highest strain energy increase. Knee flexion induced approximately ten times the normalized strain energy induced by hip adduction. Strain and strain energy were strongly correlated with the hip-joint reaction force ($R^2 = 0.90$–0.99; $p < 0.05$) for all activities, though the peak load location was activity-dependent. None of the exercises was likely to cause fracture. Femoral neck mechanics is activity-dependent and maximum isokinetic hip-extension and knee-flexion exercises are possible alternative solutions to impact activities for improving femoral neck strength.

1. Introduction

Osteoporosis is characterized by low bone density, micro-architectural deterioration of bone tissue and an increased risk of fragility fractures (Cooper and Melton, 1992). Hip fragility fractures carry the highest morbidity and mortality rates amongst the elderly, and post-menopausal women have the highest risk of fracture (Sernbo and Johnell, 1993). The prevention of hip fractures is a critical step in minimizing their burden, and physical activity is considered a key preventative solution to maintaining bone strength by promoting femoral neck bone formation (Petit et al., 2009).

Bone mineral density (BMD) remains relatively constant in response to common activities of daily living that involve low loads (Nikander et al., 2010), while activities with higher loads have been suggested to promote bone formation (Kohrt et al., 1997; Rhodes et al., 2000). There is some degree of variability in the literature regarding what constitutes a high-load activity; for example, it has been suggested that walking and jumping are high-load tasks because they generate ground reaction forces between 1 and 3 times body weight (BW) respectively (Kohrt et al., 1997), whereas resistance exercises are considered high-load when the resistance exceeds 75% of that achieved during a single maximum voluntary contraction (Rhodes et al., 2000). The reported effect of physical activity interventions on BMD is inconsistent (Bailey and Brooke-Wavell, 2010; Dornemann et al., 1997; Ebrahim et al., 1997; Kohrt et al., 1997; Lohman et al., 1995), and a comparison of these studies suggests that it is not simply attributable to differences in load magnitudes. Daily hops have been found to increase BMD by 2.8% (Bailey and Brooke-Wavell, 2010), while a more complex exercise program that included walking, jogging, and stair climbing increased BMD by 4.3% (Kohrt et al., 1997). Targeted strength exercises, typically executed using gym-based equipment, induced up to a 2% BMD increase (Lohman et al., 1995), although it is worth noting that studies investigating strength exercises are either not well described (Lohman et al., 1995) or have included only a subgroup of possible hip and/or knee strength exercises (Dornemann et al., 1997). The differing, and at times counterintuitive, response of bone to

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physical activities complicates the development of exercise interventions for the prevention of hip fractures. While it has been suggested that the varying BMD response is related to the fact that alternative physical activities load the femoral neck in different ways (Martyn-St James and Carroll, 2006), a quantitative comparison and ranking of a variety of physical activities based on their effect at the femoral neck has yet to be conducted. We suggest that this ranking may provide a useful framework from which exercise interventions can be developed with the long-term aim of providing more consistent results in longitudinal studies.

Computational modeling is the only viable method for estimating in vivo strain within the intact and undisturbed femoral neck. Indeed, the determination of which physical activities optimize loading of the femoral neck requires knowledge of the loads applied to the bone by muscle and joint reaction forces as well as the bone geometry and mechanical properties. Subject-specific loads have been calculated using musculoskeletal models (Correa et al., 2010; Jonkers et al., 2008; Martelli et al., 2011; Pandy and Andriacchi, 2010). Finite-element models based on computed tomography (CT) scans have been used to obtain subject-specific estimates of femoral neck strain (Keyak et al., 1993; Schileo et al., 2007), fracture load (Dall'ara et al., 2012; Schileo et al., 2008b), and mechanically-driven BMD changes (Huiskes et al., 1987; Weinans et al., 1993). Musculoskeletal and finite-element modelling approaches can be integrated to investigate the effects of different physical activities on femoral neck mechanics.

The aim of this study was to calculate and rank the potential for low- and high-load physical activities that have been suggested to offset the detrimental effect of osteoporosis and to assess the risk for femoral neck fractures during such activities (Kohrt et al., 1997; Rhodes et al., 2000). Femoral neck strain energy and tensile strain were used as the two metrics for bone formation (Huiskes et al., 1987) and fracture (Schileo et al., 2008b) and were determined by combining experimental gait data with computational musculoskeletal modeling and finite-element analysis.

2. Materials and methods

A lower-limb musculoskeletal model and a finite-element model of the right femur were generated from published data (Testi et al., 2010) from a single donor (female, 81 year-old, height = 167 cm, weight = 63 kg). Muscle and hip-joint reaction forces during selected activities were calculated using the musculoskeletal model, and applied to the finite-element model (Fig. 1) to obtain estimates of bone formation (strain energy) and fracture (tensile strain).

2.1. Physical activities

Fifteen weight-bearing activities and resistance exercises were categorized as low- and high-load physical activities (Table 1). High-load weight-bearing activities were assumed to generate a ground reaction force above 1 BW (Kohrt et al., 1997), while resistance exercises were considered high-load when the resistance exceeded 75% of that achieved during a single maximum voluntary contraction (Rhodes et al., 2000).

Weight-bearing activities were studied using joint-motion and ground-reaction-force data recorded from two healthy adult female volunteers that were body-matched to the donor. The first publicly available (Testi et al., 2010, www.physiomespace.com) dataset comprised experimental data recorded for five different activities: stair ascent, stair descent, rising from and lowering into a chair, step up, and level walking (Table 1, Subject A: 25 years old, 165 cm height, and 57 kg weight). The second dataset comprised of experimental data recorded at the University of Melbourne Biomotion Laboratory for three additional tasks: one-legged maximum-distance long jump, two-legged maximum-height jump, and lifting a 10 kg weight from the ground to an upright position using both hands (Table 1, Subject B: 24 years old, 167 cm height, 62 kg weight). Ethics approval was obtained from the institutional Human Research Ethics Committee.

Data reported by Pyka et al. (1994) were used to assess the effect of resistance exercises (Table 2). Data included the maximum forces exerted during concentric contractions in the sagittal and frontal planes about the hip joint and in the sagittal plane about the knee joint for a cohort of elderly men and women aged between 61- and 78-years-old.

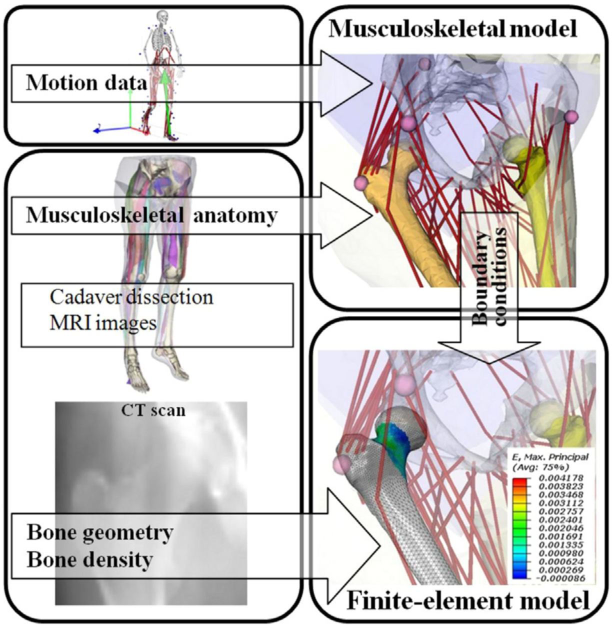

Fig. 1. Overview of the modeling pipeline. Forces acting on the femur were calculated using the donor musculoskeletal model (top right) derived from magnetic resonance images (middle left) and using input motion data collected on body-matched volunteers (top left). The finite-element model of the right femur (bottom right) was generated from computed tomography (CT) data (bottom left) obtained from the same donor and used to calculate femoral neck tensile strain and strain energy during low- and high-load activities.

2.2. Musculoskeletal model

Muscle and joint reaction forces were calculated using a lower-limb musculoskeletal model based on a previous study (Martelli et al., 2011). The body was modelled as a 13-segment, 15 degree-of-freedom (DOF) articulated system, actuated by 84 muscle-tendon units. The skeletal anatomy was extracted from the donor's full-body CT scan. Inertial properties of each segment were derived from the CT images assuming homogeneous density properties for both the hard (1.42 g/cm^3) and soft (1.03 g/cm^3) tissues (Dumas et al., 2005). Peak isometric muscle forces were calculated using the physiological cross-sectional area of each muscle extracted from magnetic resonance images obtained from the donor and assuming a value of 1 MPa for the specific tension of muscle (Glitsch and Baumann, 1997). Values for optimum muscle-fibre length and tendon slack length reported by Delp et al. (1990) were scaled to the donor's anatomy by matching the joint angles at which each muscle exerted its maximum isometric force. All simulations were performed using an open-source musculoskeletal modeling environment called OpenSim (Delp et al., 2007).

Weight-bearing activities were simulated by applying an inverse kinematics algorithm to calculate the joint positions for a representative trial of each physical activity followed by a calculation of the net joint torques. A static optimization problem was solved to decompose the net joint torques amongst the muscles by minimizing the weighted squared sum of muscle activations.

Resistance exercises were simulated using the external forces reported by Pyka et al. (1994) (Table 2). The external forces were decreased by 38% to account for the lower-than-average (Ward et al., 2009) muscle volumes of the donor. For each resistance exercise, the scaled force was applied to the model in the anatomical pose and kept constant in the local frame over a physiological range of motion (Roach and Miles, 1991) while imposing a low constant joint speed (<7 deg/s). The resulting joint torques were consistent with those generated in age-matched subjects during muscle strength tests (Steinhilber et al., 2011; Tan et al., 1995). The same procedure described for the weight-bearing activities was used to decompose the net joint torques amongst the muscles.

The hip-joint reaction forces calculated in the model were compared with measurements of hip-joint reaction forces obtained from elderly THR patients (Bergmann et al., 2001; www.orthoload.com) for level walking, stair ascent, stair descent, and rising from and lowering into a chair.

2.2.1. Finite-element model

A finite-element model of the right femur was created from CT images (General Electric Co., USA, tube current: 160 mA, tube voltage: 120 kVP) of the donor (Testi et al., 2010; www.physiomespace.com). The bone geometry was segmented from the CT scan using medical image processing software (Amira©, Visage Imaging GmbH, USA). Bone tissue was modeled using 10-node tetrahedral elements. Bone