Using the flexible multibody approach to estimate bone strain during physical activity: quantifying osteogenic potential

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Abstract. *As the stimulus for bone adaptation, bone strain is an indicator of the effectiveness of bone strengthening exercise. A flexible multibody analytical approach was used to calculate leg bone strain based on motion capture data taken as a human subject performed a number of exercises. Four typical leg strengthening exercises were studied: leg press, knee flexion, knee extension, and squats with focus on the tibia. Walking was included as a reference. Mechanostat theory was applied to quantify the osteogenic potential of each exercise.*

Keywords: bone strength; component mode synthesis; CT.

1 INTRODUCTION

The human skeleton is a weight bearing structural mechanical system. As it fulfills its lifelong function, skeletal bone mass is constantly being adjusted it to accommodate changing demands. Increased loading promotes bone formation and reduced loading results in bone resorption. Although this optimization process is effective, our increasingly sedentary lifestyle is resulting in excessive loss of bone mass among the elderly. Loss of bone mass decreases rigidity and increases the risk of fracture. In turn, osteoporotic bone fractures heal poorly, and osteoporosis is becoming a significant public health care problem [1]. Applying effective preventative procedures [2] to delay the onset of osteoporosis and slow its progression can improve the quality of life for our growing senior population. One possible prevention method is exercise. However, choosing the most effective regimen is not straightforward and further research is needed to better understand how loads propagate through the skeletal structure in response to each exercise and how the bones respond to these loads. In short, we must better understand which exercises and which exercise programs best stimulate bone growth.

The body's bone optimization process is not completely understood. However, we know that loading plays an important role in bone formation and resorption. The mechanostat model promoted by Frost in the 1960's [3] establishes threshold strain values that distinguish regions of loading intensity. In the broad region between the lower and upper threshold values, called the *adapted state*, bone density remains constant. For strain values greater than the upper threshold, in the *overload* region, bone begins to form and bone density increases. For strain values below the lower threshold, in the *disuse* region, resorption begins taking place and bone density starts to drop.

Unfortunately, it is not easy to quantify bone strain in a living human. To measure it directly, strain gauges must be applied to the bone in the area of interest. This approach involves surgical procedures to place and then remove each measurement device. *In-vivo* strain measurement is also limited to accessible bone surfaces. It is not a feasible approach for bones tightly encased by muscle tissue such as, for instance, the femur. Furthermore, how the body responds to the aftereffects of the implantation procedure during post-op recovery can influence strain gauge readings.

On the other hand, using biomechanical computer simulation to determine bone strain relaxes those major constraints. The state of the art in this field of analysis is making it possible to calculate bone strain for any bone location with reasonable accuracy, on the surface or within the bone structure [4-6].

2 MATERIALS AND METHODS

2.1 Flexible multibody dynamics

Flexible multibody dynamics is used extensively as a tool in mechanical studies. It can account for machine element flexibility, but still offers sufficient computational efficiency to analyze the dynamics of a complex structure. The flexible multibody dynamics approach is seeing increasing use in the field of biomechanics. Unlike the finite element method, which requires computationally complex analytical models that result in prohibitively lengthy computation times, flexible multibody dynamics can simulate seconds or minutes of physical activity effectively and economically. For efficient dynamic simulation, modal reduction routines must be applied to the flexible members of a mechanical structure. These routines allow overall body behavior to be described using deformation modes, reducing the number of degrees of freedom (from thousands to tens) that must be solved for each time step [7]. In this work, we made use of the commonly used Craig-Bampton modal reduction method [8].

2.2 Modeling procedure

The multibody model for each subject skeletal structure was built in the MSC Adams (R3) general purpose multibody code using the BRG LifeMod plug-in (2008.1). The LifeMod plug-in adds a user interface to Adams that facilitates the construction and manipulation of human musculoskeletal models, makes it easier to integrate motion capture data input, and expands simulation post-processing capabilities. The human body models are built based on a database that relates structural dimensions and inertial properties to a subject's age, gender, ethnicity, weight, and height. Each model can be further adjusted as needed.

To compute dynamic bone strain response, several inputs are needed. The first of these defines how the bone structural elements move. The motion data in this study was acquired at the University of Jyväskylä using the Vicon T40 ten-camera infrared motion capture system (Vicon Motion Systems, Oxford, UK). The applied external forces also must be input to the model. For the reference walking case, these external forces were the ground reaction force measured with walking force measurement platforms. For the leg strengthening exercises, the tension of the cable supporting the equipment's resisting weights was the external force input.

A geometric bone model is needed to calculate internal bone strain. Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) provided the necessary bone geometries. The CT and MRI images were processed to build a volumetric CAD bone model. This model was converted to a finite element representation and subjected to modal analysis to produce the flexible bone model for the dynamic multibody simulation.

The simulation of each exercise began with inverse dynamics, where the analytical human model was driven by the acquired motion capture data. This made it possible to assess the initial conditions of the simulation and to define the muscle contraction patterns for the forward dynamics problem. For the forward dynamics simulation, the muscle contraction recording elements were replaced with active analytical muscle models that used, as a reference control, the contraction patterns from the inverse dynamics solution. The human model was driven by the muscle forces computed by proportional-integral-derivative (PID) controllers. This allowed realistic replication of the structural movements for each exercise case. During the forward dynamics simulation, bones were subjected to forces generated by muscles, gravity, mechanical connections, and external loads.

2.3 Studied exercises

Walking was used as a reference exercise, and two walking case studies were considered. In the first, which focused on the lower leg, tibial strains were estimated [9]. This study validated the method with respect to *in-vivo* studies, which measured strain at the midshaft of the tibia [10,11]. The second walking case focused on femoral strain. Providing *in-vivo* data from the proximal lateral aspect of the femur to compare with analytical predictions, this case also demonstrated the suitability of the method [12].

Finally, four typical leg strengthening exercises were studied: leg press, knee flexion, knee extension, and squats with weights to focus on the tibia. Knee flexion and extension and the leg press are performed in a seated position. Their simulation does not require a balance control algorithm. Because the human subject is stably positioned, they also allow for higher force output. Squatting with weight, on the other hand, is a fully three-dimensional exercise, which requires activation of most of the muscle groups in the body, not only to support the load, but also to maintain balance.

Figure 1 presents the studied cases. The top row in the figure illustrates the stationary exercises. The bottom row shows the exercise cases requiring balance.

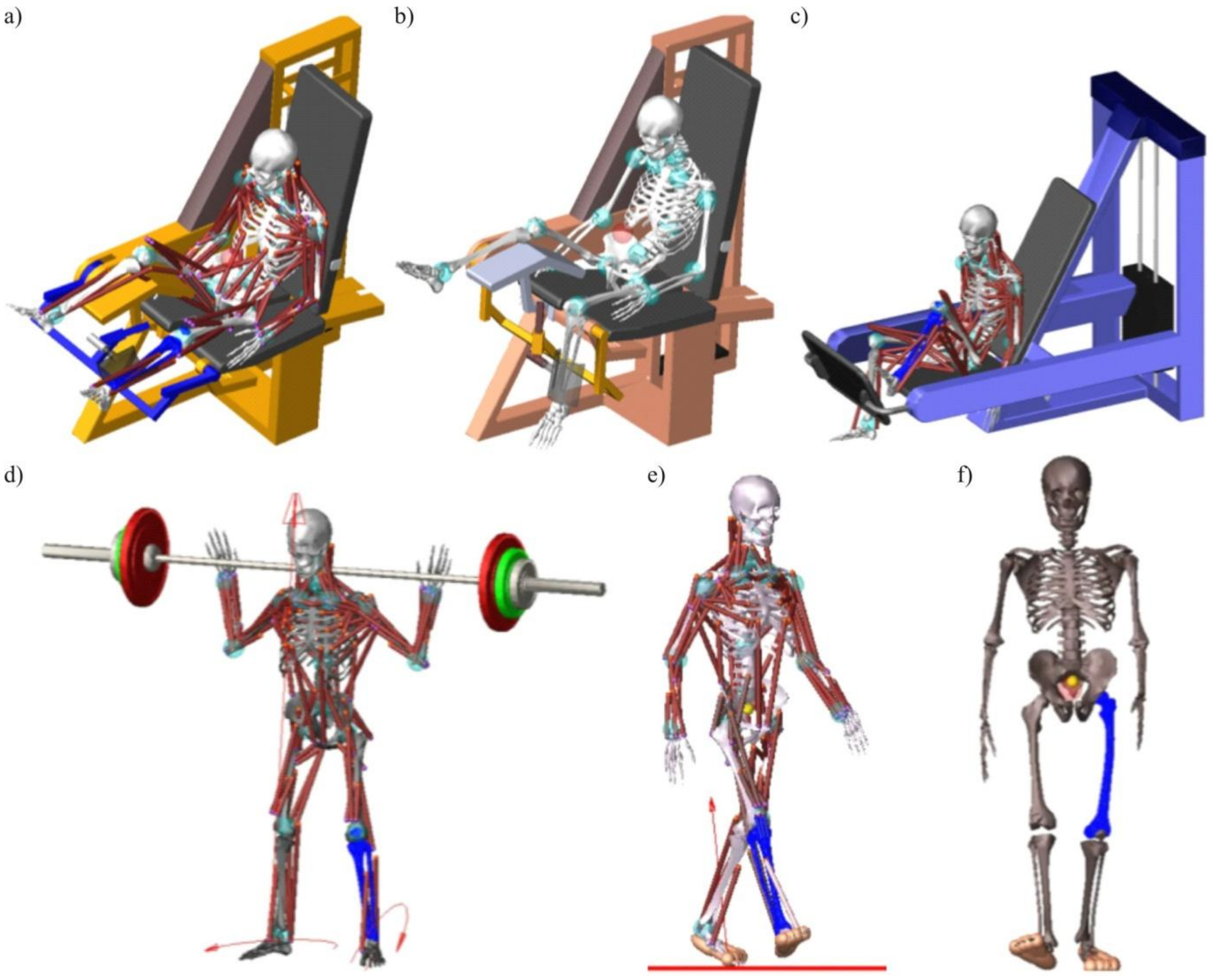

Figure 1 - Simulated exercises: a) knee flexion, b) knee extension, c) leg press, d) squatting, e) walking, lower leg study, f) walking, upper leg study

3 CONCLUSIONS

The calculated strain results indicate that knee flexion, similarly to walking, is a low strain exercise for the tibia. Knee extension, on the other hand, is optimal for tibia strengthening according to mechanostat theory [3]. Squatting with weights induces strain in the tibia that is relatively moderate, because two legs share the load. Leg presses, performed with only one leg, induce high values of tibial strain. In each exercise for this study, the human subject exerted as much force as possible or near maximum force. Nonetheless, loading varied significantly across the exercise cases.

In general, the predicted strain results for the studied exercises are comparable to values obtained *in-vivo* for running. Axial strain values for running measured at the midshaft of the tibia were in the range of -2456 to 1,243 με [13]. The same study gives values for treadmill running that range from -956 to 959 με. In this current study at the same tibial location, predicted strain values ranged from -1813 to -579 με for high-speed squatting and from -2457 to -477 με for low-speed squatting. Therefore, squatting with weights seems to result in tibia strain levels in the same range as those measured in running subjects. Knee flexion produced results within the range of -142 to 787 με; comparable to running on a treadmill.

Applying mechanostat theory [3] to the results makes it possible to classify these exercises with respect to their osteogenicity. According to theory and the data, leg presses with 90 kg of load can lead to bone growth. On the other hand, squatting with 70 kg of load does not have a bone strengthening effect; neither does knee flexion. Knee extension with 30 kg of load produces strain in the *adapted state* region. Increasing the load to 40 kg and performing the exercise at high or moderate speed lifts the tibial strain values into the *overload* region, suggesting strong osteogenic potential for this exercise. Even though squatting with weights and knee flexion did not show tibial bone strengthening potential, they still might positively effect femur growth. This supposition, however, must be still verified by future studies.

The strengthening effect of the exercise depends on way the load is applied and the strength of the muscles that can actuate the bone against the load. Since the mechanical system of human bones and muscles is complex, an exercise may produce insufficient bone strengthening strain in one bone and more than adequate strain in another. In the future studies, each bone involved in each exercise case should be studied separately to identify optimal exercising regimens to target the strengthening of specific bones and at the same time to limit joint loading and possible overloading of others.

4 ACKNOWLEDGEMENTS

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