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CRITICAL LOADING DURING SERVE: MODELING STRESS-INDUCED BONE GROWTH IN PERFORMANCE TENNIS PLAYERS

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INTRODUCTION:

On September 27, 2004 Andy Roddick hit the current world record 155 mph serve in his Davis Cup match against Belarus, which set him up with three match points against Vladimir Voltchkov. By that time, at 22 years of age, Roddick had broken his own speed record for the third time. In tennis, like in almost all other high performance sports, professional athletes tend to reach their peak performance at a much younger age than they used to several decades ago. Accordingly, athletes have to start full-time practice in their early childhood that strongly overlaps with the period of skeletal and muscular development. It is the responsibility of their coaches and physicians to design efficient training programs targeted at maximal performance and minimal risk of injury. Biomechanics can play a crucial role in supporting the design of these training strategies. By predicting the functional adaptation of bones and muscles, biomechanics simulation can help to explain and eventually prevent common forms of injuries caused by chronic overuse.

It is well known that exercise-induced loads cause bone hypertrophy in the dominant arm of tennis players; this phenomenon has been documented by numerous studies of players who began play at pre-pubescent ages [1]. However, the details that describe the processes of growth and remodeling that accompany this observation are unknown [2]. Motivated by athlete college tennis players who reported chronic pain in their dominant shoulder, we aim to predict humeral growth in the stroke arm in response to high performance sport specific mechanical loads. We hypothesize that the critical load scenario that initiates bone growth and remodeling is related to maximum external shoulder rotation associated with maximum pre-stretch of the internal rotators. We model bone hypertrophy using a finite element growth model, and that simulation gives further insight into the interplay between load and biological response.

METHODS:

To test the hypothesis that peak loading conditions relevant to growth and remodeling occur during serve, we first performed video analysis of an elite-level college athlete. Based on the individual images during a serve, we identified several postures to determine critical humerus muscle forces. In particular, we focused on maximum external shoulder rotation and ball impact (Fig. 1). These postures were reproduced using an upper limb musculoskeletal model [3] in the OpenSim [4] modeling environment to determine muscle moment arms, muscle forces, and lines of action (Fig. 3). Estimated muscle forces (Fig. 4) were then applied as external forces in a finite element analysis to predict changes in bone density in response to loading [5]. The calculated density profiles were qualitatively compared to bone mass density measures of the study subject (Fig. 2).

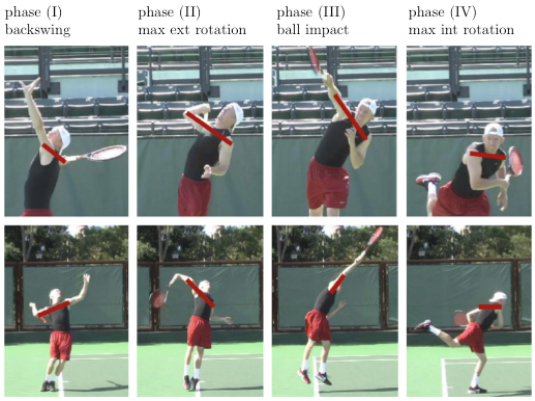

Figure 1. Phases of high speed serve. Critical forces are postulated to occur at phase (II) and phase (III).

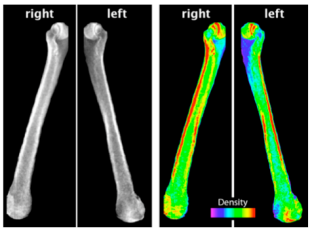

Figure 2. Humerus X-ray images of study subject. Bone mass density of 1.369 g/cm^2 (right) and 1.107 g/cm^2 (left).

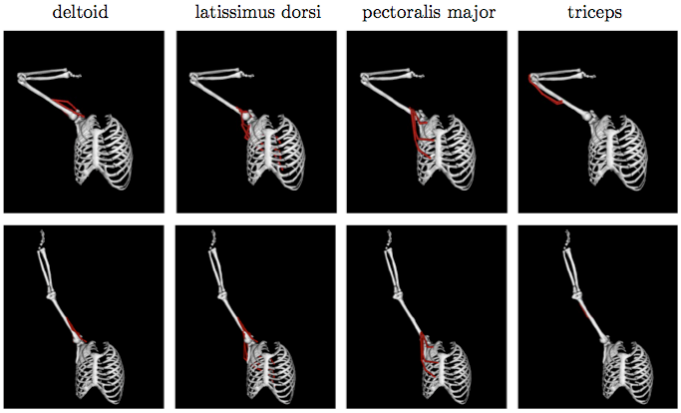

Figure 3. Relevant muscle groups for the right humerus are shown for phase (II) and phase (III).

RESULTS:

The dominant torsional loading experienced during the maximal external rotation phase of the tennis serve resulted in pronounced inhomogeneous torsional growth. Figure 5 displays the temporal evolution of the density profile in response to the muscles forces of phase (II) at maximum external shoulder rotation. This phase of the service is crucial in preparation for a high speed serve. It is dominated by an eccentric pre-stretch of the internal rotators that aims at storing elastic energy in the pectoralis major and the latissimus dorsi. The external shoulder rotation during phase (II) is so extreme that the related posture can only be achieved dynamically. The primary goal is to recover the stored muscle energy during the concentric phase of muscle shortening prior to ball impact and thereby maximize racket acceleration. In fact, 40% of the racket velocity can be attributed to upper arm internal rotation. It is thus not surprising that this load case generates incredibly large muscle forces and cause significant humeral hypertrophy.

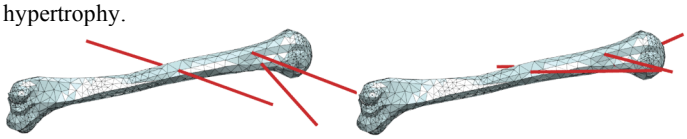

Figure 4. Force magnitudes and directions determined from serve postures are shown on humerus.

The tremendous forces of 1490N and 1275N generated by the pectoralis major and the latissimus dorsi group cause a critical rotational loading. Twisted bone growth is a natural consequence of this loading pattern. The density profiles of figure 5 clearly display the characteristic twisted bone growth profile that was found in tennis players, baseball pitchers and handball players. Torsion induced humeral hypertrophy generates increased bone growth all along the humeral axis. The computationally predicted density profiles nicely agree with experimental findings and thus suggest that maximum external should rotation indeed plays a significant role in the functional adaptation process of high performance tennis players.

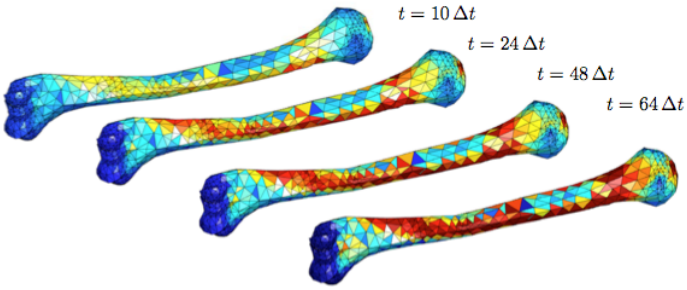

Figure 5. Time sequence of density adaptation in maximum shoulder rotation agrees with observed density pattern.

CONCLUSION:

These results provide additional insight and improved understanding of complex phenomena associated with torsional growth along the humeral shaft. This method of predicting bone growth using musculoskeletal modeling and finite element growth models could be of equal benefit to high performance athletes and patients with degenerative bone diseases. Based on patient-specific studies, optimized training strategies can be developed to promote bone growth.

Overall, there is a more general potential to the present study and its social impact is not exclusively restricted to improve performance in competitive sports. The described techniques to initiate bone growth through strategically targeted loading can provide guidelines to develop patient-specific training schedules for the elderly population. As such, the present theory could help to design physical therapies to increase bone mineral density in treatment of degenerative bone diseases such as osteoporosis. We believe that the proposed multilevel analysis strategy has a significant potential to provide further understanding of the effects of sport induced critical loading on skeletal development and functional adaptation.

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