Fakultät Maschinenbau
Lehrstuhl für
Maschinenelemente und Konstruktionslehre
Prof. Dr.-Ing. Dipl.-Wirt. Ing. Tim Sadek

RUHR
UNIVERSITÄT
BOCHUM

RUB

Sverdlova, N.; Witzel, U.

Principles of determination and verification of muscle forces in the human musculoskeletal system: muscle forces to minimise bending stress

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Abstract

While there are a growing number of increasingly complex methodologies available to model geometry and material properties of bones, these models still cannot accurately describe physical behaviour of the skeletal system unless the boundary conditions, especially muscular loading, are correct. Available in vivo measurements of muscle forces are mostly highly invasive and offer no practical way to validate the outcome of any computational model that predicts muscle forces.

However, muscle forces can be verified indirectly using the fundamental property of living tissue to functional adaptation and finite element (FE) analysis. Even though the mechanisms of the functional adaptation are not fully understood, its result is clearly seen in the shape and inner structure of bones. The FE method provides a precise tool for analysis of the stress/strain distribution in the bone under given loading conditions.

The present work sets principles for the determination of the muscle forces on the basis of the widely accepted view that biological systems are optimized light-weight structures with minimised amount of unloaded/underloaded material and hence evenly distributed loading throughout the structure. Bending loading of bones is avoided/compensated in bones under physiological loading. Thus, bending minimisation provides the basis for the determination of the musculoskeletal system loading. As a result of our approach, the muscle forces for a human femur during normal gait and sitting down (peak hip joint force) are obtained such that the bone is loaded predominantly in compression and the stress