Exploring In Vivo 3D Joint Impairments Using MRI-Based Dynamic Joint Models

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INTRODUCTION

The Virtual Functional Anatomy (VFA) project is designed to fill the important knowledge gap that exists in the relationship between functional movement limitations and impaired joint structure and function. Our current focus is to develop and ultimately validate a combined set of tools that will enable the accurate and precise measurement, analysis and visualization of three-dimensional (3-D) static and dynamic musculoskeletal anatomy (i.e., bone shape, skeletal kinematics, tendon and ligament strain, muscle force, and joint space). This project combines MR imaging capabilities with a highly accurate, imaging-based measurement and analysis techniques for the non-invasive quantification of complete joint anatomy and tissue dynamics during functional movements. This requires the development of methodologies for creating 3D digital images of loaded and moving joint tissues (bone, cartilage, and connective tissues) in order to reveal joint contact patterns and tissue loads. The variability of bone shape and the sensitivity of defined joint attitude (translation and rotation of one bone relative to another) to osteo-based coordinate system definition are being evaluated. These capabilities are being developed to document and evaluate the function of normal and impaired joint structures (e.g., Cerebral Palsy, Ehlers Danlos syndrome and patellar maltracking syndrome) under simulated conditions experienced during activities of daily living. Recently, this work has concentrated on four primary project areas: 1) VFA tool development, 2) In vivo normal and impaired knee joint function, 3) In vivo ankle joint function and 4) The quantification of bone shape.

METHODS

The cornerstone of quantifying 3D joint dynamics is the General Electric (GE) fast phase contrast (fast-PC) imaging sequence, which acquires a series of images over time development.
depicting the anatomy with correlated measures of the 3D velocity for each pixel within the imaging plane. During a fast-PC acquisition subjects cyclically move their joint through a specified range of motion at a typical rate of 35 cycles/minute. Next, the 3D attitude for each bone within the joint and muscular displacements over the movement cycle are quantified through integration of the velocity data. Based on the attitude of the bones and muscular displacements; the finite helical axis, tendon moment arms and tendon strain are defined. By registering the dynamic data with high quality static 3D MR images, ligament strains and cartilage contact patterns can be determined. In addition to the dynamic imaging, methods are under development for the 2D and 3D quantification of bone shape.

Currently normative databases for complete knee joint (n=34), inclusive of the patellofemoral and tibiofemoral joints, and for the hindfoot (n=22), inclusive of the talocrural and subtalar joints, have been established. Using these data the finite helical axes of these joints and the strain and moment arm of the patellar and Achilles’ tendon have been quantified. Beginning with this baseline, the changes in joint kinematics due to impairments (Cerebral Palsy, Ehlers Danlos syndrome, patellar maltracking, ACL loss) are being explored.

RESULTS AND DISCUSSION

By creating highly accurate and precise databases for knee and ankle joints, specific trends have come to light that have not been seen before. It was determined that the joints of the ankle do follow a coupled rotation (supination or pronation), but primary rotations occur at joints opposite to clinical definitions. It was determined that the knee joints do not follow a coupled rotation and that individual subjects can have variable initial starting attitudes and changes in attitudes. This variability likely accounts for much of the inter-subject variability and some of the conflicting results reported in different studies. In terms of impairments, it was demonstrated that patellar maltracking was not simply a 2D problem, but alterations in kinematics could be seen in all three directions. In cerebral palsy, a lack of support for the theory of “lever-arm” dysfunction being the source of low joint torque was found. In this population there was good agreement between the kinematic results and clinical findings.

The two dimensional bone shape project defined key definitions for developing anatomical coordinate systems for the knee and ankle joints. It also highlighted potential sources of error in previous static and kinematic MRI studies. It was found that a slight rotation or translation of the knee joint relative to the imaging plane resulted in significant differences in six key parameters typically used in clinical imaging to define patellofemoral impairments. The 3D bone shape project has demonstrated that in order to better quantify local shape variations, the local and global shape variations must be accounted for separately.

SUMMARY/CONCLUSIONS

The VFA toolbox is an accurate and precise tool for acquiring data with which to study the effects of impairments on the musculoskeletal system at the joint level. The fact that direct links have been seen between the VFA outputs and clinical evaluations implies that this tool has the potential for becoming a key clinical analysis package. The bone shape project will allow for more precise average bone models and for the quantification of variations in bones on both the local and global scale.