Biomechanical consequences of gait impairment at the ankle and foot

Injury, malalignment, and co-contraction

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Abstract

The human foot contributes significantly to the function of the whole lower extremity during standing and locomotion. Nevertheless, the foot and ankle often suffer injuries and are affected by many musculoskeletal and neurological pathologies. The overall aim of this thesis was to evaluate gait parameters and muscle function change due to foot and ankle injury, malalignment and co-contraction. Using 3D gait analysis, analytical analyses and computational simulations, biomechanical consequences of gait impairment at the ankle and foot were explored in ablebodied persons and in patient groups with disorders affecting walking.

We have characterized gait patterns of subjects with ankle fractures with a modified multi-segment foot model. The inter-segmental foot kinematics were determined during gait in 18 subjects one year after surgically-treated ankle fractures. Gait data were compared to an age- and gender-matched control group and the correlations between functional ankle score and gait parameters were determined. It was observed that even with fairly good clinical results, restricted range of motion and malalignment at and around the injured area were found in the injured limb.

Moment-angle relationship (dynamic joint stiffness) - the relationship between changes in joint moment and changes in joint angle - is useful for demonstrating interaction of kinematics and kinetics during gait. Ankle dynamic joint stiffness during the stance phase of gait was analyzed and decomposed into three components in thirty able-bodied children, eight children with juvenile idiopathic arthritis and eight children with idiopathic toe-walking. Compared to controls, the component associated with changes of ground reaction moment was the source of highest deviation in both pathological groups. Specifically, ankle dynamic joint stiffness differences can be further identified via two subcomponents of this component which are based on magnitudes and rates of change of the ground reaction force and of its moment arm. And differences between the two patient groups and controls were most evident and interpretable here.

Computational simulations using 3D musculoskeletal models can be powerful in investigating movement mechanisms, which are not otherwise possible or ethical to measure experimentally. We have quantified the effect of subtalar malalignment on the potential dynamic function of the main ankle dorsiflexors and plantarflexors: the gastrocnemius, soleus and tibialis anterior. Induced acceleration analysis was used to compute muscle-induced joint angular and body center of mass accelerations. A three-dimensional subject-specific linkage model was configured by gait data and driven by 1 Newton of individual muscle force. The excessive subtalar inversion or eversion was modified by offsetting up to ±20° from the normal subtalar angle while other configurations remain unaltered. We confirmed that in normal gait, muscles...
generally acted as their anatomical definitions, and that muscles can create motion in many joints, even those not spanned by the muscles. Excessive subtalar eversion was found to enlarge the plantarflexors' and tibialis anterior's function.

In order to ascertain the reliability of muscle function computed from simulations, we have also performed a parametric study on eight healthy adults to evaluate how sensitive the muscle-induced joints' accelerations are to the parameters of rigid foot-ground contact model. We quantified accelerations induced by the gastrocnemius, soleus and tibialis anterior on the lower limb joints. Two types of models, a ‘fixed joint’ model with three fixed joints under the foot and a ‘moving joint’ model with one joint located along the moving center of pressure were evaluated. The influences of different foot-ground contact joint constraints and locations of center of pressure were also investigated. Our findings indicate that both joint locations and prescribed degrees-of-freedom of models affect the predicted potential muscle function, wherein the joint locations are most influential. The pronounced influences can be observed in the non-sagittal plane.

Excessive muscle co-contraction is a cause of inefficient or abnormal movement in some neuromuscular pathologies. We have identified the necessary compensation strategies to overcome excessive antagonistic muscle cocontraction at the ankle joint and retain a normal walking pattern. Muscle-actuated simulation of normal walking and induced acceleration analysis were performed to quantify compensatory mechanisms of the primary ankle and knee muscles in the presence of normal, medium and high levels of co-contraction of two antagonistic pairs (gastrocnemius-tibialis anterior and soleus-tibialis anterior). The study showed that if the co-contraction level increases, the nearby synergistic muscles can contribute most to compensation in the gastrocnemius-tibialis anterior pair. In contrast, with the soleus-tibialis anterior co-contraction, the sartorius and hamstrings can provide important compensatory roles in knee accelerations.

This dissertation documented a broad range of gait mechanisms and muscle functions in the foot and ankle area employing both experiments and computational simulations. The strategies and mechanisms in which altered gait and muscles activation are used to compensate for impairment can be regarded as references for evaluation of future patients and for dynamic muscle functions during gait.

Keywords

muscle function, gait analysis, induced acceleration, foot kinematics, dynamic joint stiffness