SUMMARY

An in silico simulation environment for performing platform perturbation experiments was developed to test the hypothesis that crouching improves postural stability and that increased stability is associated with deeper crouch. Stability was measured from the time-to-fall after a disturbance was applied to a skeletal model in a standing pose. The simulations revealed improvements in postural stability with increasing crouch. Larger improvements were seen for anterior-posterior disturbances than right-left disturbances for the same pose. The results suggest that adopting a crouch posture can serve to stabilize the body and may explain, in part, why individuals with neurological impairments such as cerebral palsy, stroke, and traumatic brain injury, exhibit crouch gait as a common movement abnormality in spite of a wide range of impairment etiologies.

INTRODUCTION

Crouch gait is a common movement disorder in a heterogeneous group of patients including cerebral palsy, stroke and traumatic brain injury populations. Why crouch gait is common in diverse patient populations with different etiologies remains unclear. It has been suggested that these individuals may select a crouch posture for the same reasons we might crouch on a surf-board or when walking into a dark room–to bolster stability when facing unforeseen disturbances. The question remains, however, whether adopting a crouch posture improves postural stability when faced with disturbances since there is evidence that experimental measurements of center-of-pressure paths deviate in impaired subjects, but that they do not correspond to the likelihood of falling [1]. Therefore, the aim of this study is to test if a crouch posture improves postural stability, defined as the ability to remain standing in the presence of disturbances.

METHODS

The effects of posture alone cannot be separated from the confounding effects of reflexes and motor-control in in vivo experiments; therefore, a postural perturbation simulator was developed using OpenSim [2] to perform in silico postural stability experiments. To isolate the effect of posture on stability, a generic 3D model of the lower-extremities and trunk, without muscles and passive structures, was placed on a translating platform. Contact between the feet and the platform was modeled with deformable contact spheres placed on the calcaneous, first and fifth metatarsal heads, and the first distal phalange of each foot. Contact spheres generated forces in proportion to their deformation when pressed against the platform surface (Figure. 1). The model’s posture was varied from upright to crouched, with postures corresponding to 1, 15, 30 and 45° of knee flexion. Angles for all other joints were determined via an optimization to locate the center-of-pressure at the center of the base of support defined by the centroid of the contact spheres. The pose also satisfied the constraint of no residual forces (for the 6 degrees-of-freedom of the pelvis) from a statics analysis, while determining the joint torques necessary to maintain a static pose. In each case, stance width of the pose was maintained to isolate the effects of crouch. The disturbance measure was the anterior-posterior and right-left displacement of the platform prescribed by a step function with a 100ms transition time. Forward dynamics simulations with applied disturbances were used to assess the stability of each posture from the time-to-fall, $T$, required for the center-of-mass to move outside of the base of support. A stability index, $S = 1 - e^{-T}$ was adopted so that a value of 1 indicated that the model did not fall (was stable) and $S < 1$ described the degree of instability with zero being the most unstable (i.e. no time elapsed from the disturbance to fall).
To isolate the effect of posture (without neuromuscular control) two conditions were tested for each posture: 1) joints free (held by constant static torques), and 2) leg and back joints locked. In reality, we would expect the effect of passive structures within and surrounding the joint to yield results that lie between these two extremes.

RESULTS AND DISCUSSION

In (C & D) the range of disturbances where the model is stable (index = 1) is presented. Anterior and rightward are positive.

Simulations confirmed that crouch postures are more stable than an upright posture. The model with free joints was unstable for all postures, but greater instability resulted from less crouch (Figs. 2A&B) and anterior disturbances (Fig. 2A). Locking the joints created stable regions for each posture and stability progressively improved with increasing knee-flexion for the anterior-posterior case (Fig. 2C) but had minor effects for right-left disturbances (Fig. 2D).

The asymmetry in anterior-posterior results can be explained by the asymmetrical shape of the feet, where the distance of the toes to the ankle resists falling forward due to posterior displacements of the platform better than the heel can resist tipping backwards. In fact in the locked case anterior-posterior disturbances that caused the model to fall, often did so by causing the model to fall backwards even in the case of posterior disturbances due to subsequent roll-back onto the heels. Stability improvements due to crouch correspond with increasing anterior-displacement and lowering the height of the center-of-mass with respect to the heels. Right-left disturbances, in contrast, showed a symmetric response. Although lowering the center-of-mass could improve stability, the decreased effective inertia about the lateral edge of the feet reduces the resistance to lateral tipping such that crouch had little net effect on the range of stability for right-left disturbances with the joints locked (Fig 2D).

CONCLUSIONS

A crouch posture improves postural stability in response to both anterior-posterior and right-left disturbances when joints are not locked. Even when the model is unstable (i.e., it falls after some time) the crouch posture’s time-to-fall is greater, which provides the opportunity to employ corrective strategies such as stepping. In both conditions, joints free and locked, the crouch posture yields greater stability over a broader range of anterior-posterior disturbances. This suggests that structures that resist joint motion such as joint friction and viscosity, ligaments, passive muscle forces and even contractures move the postural model towards greater stability. Adopting a crouch posture to improve stability comes at a cost; joint moments, and hence muscle forces, in a crouch posture are larger, requiring greater metabolic demands. Recognizing that individuals with cerebral palsy and other neurological impairments may adopt a crouch posture to improve stability suggests that treatment strategies that target balance may help individuals to adopt a more upright posture and gait.

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