Balance control is simplified by muscle-skeletal leg design

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1 Motivation and state of the art

Different gaits with upright body configurations make human bipedal locomotion unique [1]. Upper body balance is key to human locomotion. To balance, humans may control the direction of the ground reaction force [2] and the center of pressure, either continuously or step by step. Older infants learn standing and walking upright while holding tight to stable objects [3], thereby simplifying balance by additional forces exerted at upper limbs. It is not clear how humans acquire their extraordinary balance skills. The mechanics of the segmented leg are not yet well understood but prerequisite for understanding neuro-muscular co-ordination [4]. Here we propose that design features related to balance may have led to evolutionary adaptation of leg geometry and muscle architecture.

2 Own approach

The ground reaction force can be decomposed in a force component pointing from center of pressure to center of mass and a perpendicular component. While the former is mainly associated with repulsion, the latter is associated with torques about the center of mass (postural balance) and propulsion. A virtual prismatic leg – connecting hip and ankle – with foot can create the same ground reaction force. It approximates the described force decomposition and respective functions with its axial and perpendicular force components. In this view, the function of the leg can be decomposed into an axial leg function (force production along virtual leg axis, measurement of leg length) and a rotational leg function (non-axial leg force production, swing leg alignment, measurement of leg angle).

To achieve efficient and versatile movements, humans would benefit from separate access to the described leg functions. For example, with bouncier tasks the amplitude of vertical energy increases but rotational and axial leg forces do not increase in proportion [5]. Direct mechanical access to the leg functions would simplify their adjustment. Technical solutions exist which allow independent access to such axial and rotational leg function (e.g. [6]; ATRIAS, http://mime.oregonstate.edu/research/drl/robots/). It is however not clear how such access could be implemented in the redundantly actuated [7], segmented human leg.

3 Current results and best possible outcome

The key result of our static analysis of the segmented leg is, that equal shank and thigh lengths, and two-joint leg muscles attached with moment arm ratios of 2:1 for hip and knee or ankle and knee, respectively, provide access to the rotational leg function independent of knee angle. These muscles do not only actuate the virtual prismatic leg, but also measure its orientation with respect to the body (thigh muscles) and with respect to the ground (shank muscle). The predicted ratios are approximated in nature close enough to propose that balance control is simplified by the architecture of the human leg. The high-dimensional segmented body can be accessed like a simple virtual model with a limited number of functional degrees of freedom. Leg geometry in combination with two-joint muscles provides a steering mechanism like a steeringwheel to adjust ground reaction force direction and center of pressure without affecting axial leg force.

References

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