JOINT STIFFNESS REQUIREMENTS IN A MULTI-SEGMENT STANCE MODEL

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INTRODUCTION

Currently, there is a vivid debate on the control mechanisms involved in human stance, in which the required and available ankle joint stiffness play a key role. Ankle stiffness values are typically discussed in the context of a one-segment stance model. Considering other joints as well, in particular the knee and the hip, it is found that the ankle stiffness should be substantially higher than the one-segment model suggests.

METHODS

In an *n*-segment model of the standing human moving in the sagittal plane, the gravitational potential energy $U_g(\varphi_1,...,\varphi_n)$ can be expressed as a function of the joint angles φ_i. The Hessian (second derivative matrix) of U_g is $\boldsymbol{G}$, the joint stiffness matrix due to gravity, which typically has negative values. The joint stiffness matrix $\boldsymbol{K}$ due to intrinsic muscle-tendon properties and reflexive control, when symmetric, can be considered the Hessian of an elastic energy potential function $U_k(\varphi_1,...,\varphi_n)$. A quasi-static requirement for stability is that the Hessian of the total potential energy, i.e., $\boldsymbol{G}+\boldsymbol{K}$, has all positive eigenvalues. We consider only local control of the joints, where $\boldsymbol{K}$ is a diagonal matrix with local joint stiffness values K_i at the diagonal. At the boundary of the region of stabilizing K_i the eigenvalues of $\boldsymbol{G}+\boldsymbol{K}$ become zero. Hence this boundary can be found by determining the combinations of K_i for which $\det(\boldsymbol{G}+\boldsymbol{K})$ equals zero. Analytical expressions can be obtained for systems up to at least order 3.

Besides these boundaries, as scalar measures we use the minimum required stiffness: 1) when all joint stiffnesses are equal, $K_i = K_0$; 2) when all joint stiffnesses exceed their single-joint requirement by the same amount, $K_i = -G_i+\Delta K_0$. Here G_i is the gravitational stiffness for joint *i* when all other joints are considered fixed. Model parameters are based on Winter (1979); resulting values of the G_i are indicated in Table 1.

Table 1 (left). *Gravitational stiffness per joint, in Nm/rad.*
Table 2 (right). *Measures for the required joint stiffness in several multi-segment stance models. All values in Nm/rad.*

joint	G_i
ankle	-754
knee	-432
hip	-160
neck	-8
shoulder	25

model	K_0	ΔK_0
ankle	754	0
ankle-hip	794	160
ankle-knee	1054	432
ankle-knee-hip	1106	528
ankle-knee-hip-neck	1106	529
ankle-knee-hip-shoulder	1107	532

RESULTS AND DISCUSSION

In a one-segment model, stability requires that $K_{ankle}+G_{ankle}>0$; i.e., the ankle joint stiffness must be at least 754 Nm/rad. However, in a two-segment ankle-hip model stability is not guaranteed when $K_{ankle}>754$ Nm/rad and $K_{hip}>160$ Nm/rad, the single-joint requirements for each joint separately. The actual stability boundary is an arm of a hyperbola with $K_{ankle}=754$ Nm/rad and $K_{hip}=160$ Nm/rad as asymptotes. As a result of the interaction between segments, typically both joint stiffnesses must exceed their single-joint requirement considerably to obtain stable stance (see Table 2). Only when one of the joints has a very high stiffness, its influence on the other joint can be ignored. When the knee is included instead of the hip, the interaction effect is stronger, as G_{knee} is larger than G_{hip}. In a three-segment ankle-knee-hip model, the stability boundary becomes a hyperbolic surface in a three-dimensional joint stiffness space (Figure 1). The numerical measures indicate that the stiffness requirements are heightened further in this case (Table 2). Modeling the head or the arms as additional segments separate from the trunk has only a minimal effect.

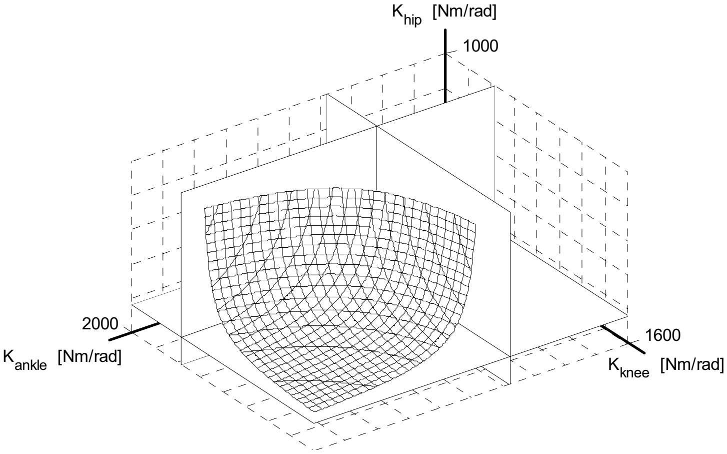

Figure 1. *Joint stiffness requirements for the ankle-knee-hip model. The straight planes represent the single-joint requirements, i.e., $K_{ankle}>-G_{ankle}$, $K_{knee}>-G_{knee}$, $K_{hip}>-G_{hip}$. Joint stiffness combinations at the near side of the curved surface actually result in quasi-statically stable stance.*

CONCLUSIONS

Inclusion of additional joints in a stance model substantially increases the local stiffness requirements for the joints already present. Assuming equal stiffness for all joints, in the ankle-knee-hip model the ankle stiffness must be at least 1106 Nm/rad, compared to 754 Nm/rad in the conventional single-segment stance model. Hence, stabilizing the inverted multi-segment pendulum of the standing human appears to be even more challenging than assumed previously.

REFERENCES

1. Winter, D.A., 1979. *Biomechanics of Human Movement.* John Wiley & Sons, New York.

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