# The effects of serial elastic actuation and upper body configuration on power consumption of a simplified planar humanoid

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## 1 Motivation

In order to make progress towards humanoids that are versatile in performing multiple types of locomotion (such as running, walking and crouching), we have been investigating various types of elastic actuation and oscillatory trajectories to reduce the power requirements on a simplified planar humanoid. Hereby, we have focused on the behaviour of series elastic actuation (SEA), since SEA allow greater shock resistance and better force control, reduce reflected inertia [3, 4] and they can be used to store and release energy to increase peak power output [2]. It also appears that humans and animals mainly make use of their series elastic elements (their tendons), rather than parallel elastic elements [1].

To find the optimal stiffness of SEA, optimizations are done for particular oscillatory trajectories. More importantly however, it is investigated how variations in motions affect the performance of SEA. We are especially interested in the effect of the upper body angle during the motion. It is observed from humans that the upper body does generally not remain vertical during a jumping or hopping motion—instead the human seems to bend his upper body when lowering his centre of mass (CoM).

## 2 Approach

A simplified planar three-link humanoid has been used that consists of three slender rigid bodies, as depicted in Fig. 1. All bodies have a mass and inertia, and so do the actuators. Analysed trajectories consist of mainly sinusoidal motions of the system's total CoM along the vertical. These motions are a practical starting point, even though they do not exactly represent the motion of a jumping human. The trajectories are altered by changing the frequency, oscillation height and upper body configuration. Two different relations are introduced to define the desired upper body configuration to make it bend down when the entire system bends down as well. The constant $c_v$ defines the desired ratio between upper body angle and lower leg angle with respect to the vertical and the constant $c_\varphi$ defines the ratio between the relative hip and knee angles.

$$c_v = \frac{\varphi_3 - \pi/2}{\varphi_1 - \pi/2} \quad c_\varphi = \frac{\varphi_3 - \varphi_2}{\varphi_1 - \varphi_2} \tag{1}$$

Both relations are tested (individually) in simulations for various $c$. An increase of $c$ implies that the upper body bends down more, although in a different manner and to a different extent for the different definitions. The upper body and lower leg angle are parallel for $c_v = c_\varphi = 1$, as is the case in Fig. 1. Note furthermore that the trajectories are derived by inverse kinematics, and do thus not imply dynamic stability. However, observed ankle torques are minimal (ideally zero because we did not model a foot) and horizontal reaction forces are zero because the centre of mass only moves along the vertical axis.

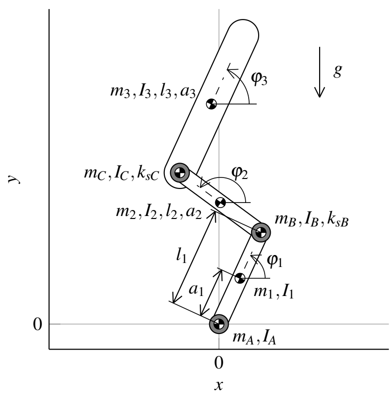


**Figure 1:** System sketch with all parameters and variables. Parameters were chosen to represent a small human with $l_1 = l_2 = 0.4$ [m], $l_3 = 0.6$ [m], $m_1 = m_2 = 10$ [kg], $m_3 = 30$ [kg]

## 3 Results

Fig. 2 shows some of the most interesting results of the simulation studies. Given a sinusoidal oscillation of the system CoM with a fixed amplitude around a specific height, it depicts the maximum absolute torque $T_{|max|}$ and average absolute power $P_{|av|}$ requirements of the actuators for various upper body configurations, oscillation frequencies and stiffnesses.

We found that the upper body configuration has a significant contribution to torque and power distributions between the knee and hip actuator. The torque and power requirements of the hip increase for increased $c_v$ and the crossover (i.e. when requirements of the knee and hip actuator are equal) is approximately at $c_v \approx 2$ for our system. This behaviour is almost independent of the frequency or stiffness.

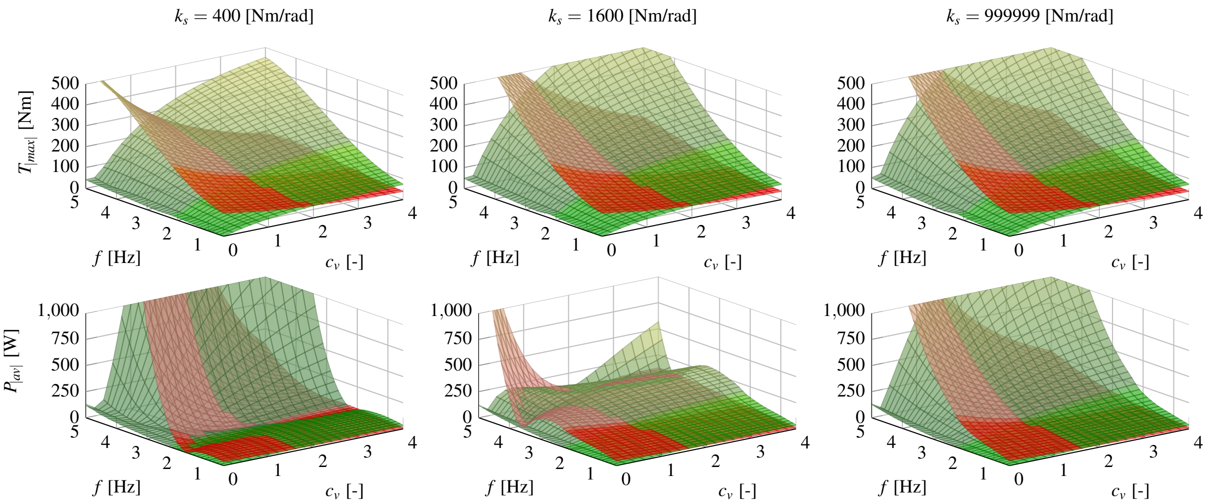


**Figure 2:** $T_{|max|}$ and $P_{|av|}$ of knee (red) and hip (green) joints as function of $f$ and $c_v$; plotted for series elastic stiffnesses $k_s = 400$ [Nm/rad] (low), $k_s = 1600$ [Nm/rad] (medium) and stiff joints. The oscillation height around which the system CoM oscillates $y_{as}$ with amplitude $A$ are fixed ($y_{as} = 0.7$ and $A = 0.05$ [m]). For systems that jump ($f > 2.23$ [Hz]), $T_{|max|}$ and $P_{|av|}$ are based solely on the stance phase and colours are saturated.

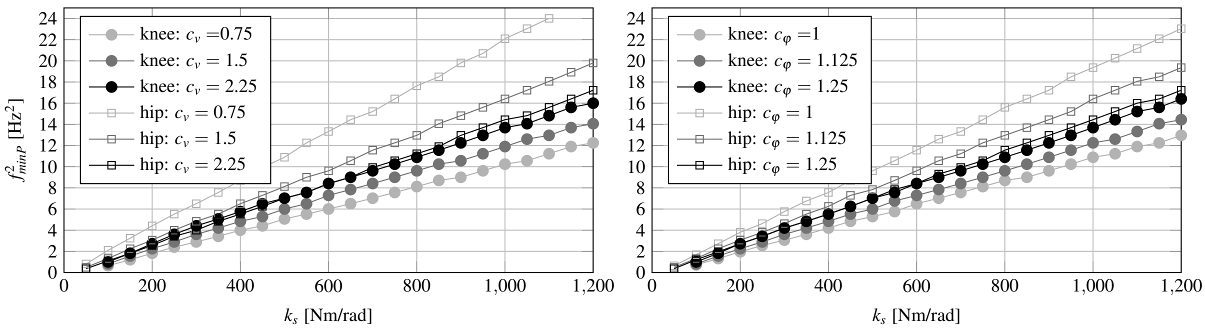


**Figure 3:** $f_{minP}$ as function of $k_s$ for knee and hip actuators and various values of $c_v$ (left) and $c_\varphi$ (right)

All frequencies lower than the frequency at which the power consumption is minimal ($f_{minP}$) also lead to power reductions, but all frequencies much higher than $f_{minP}$ lead to extreme deterioration of power requirements. Torque requirements do generally not deteriorate[1], but do also not significantly improve for the workable range of frequencies. Simulations also show that $f_{minP}$ grows approximately quadratically with the series elastic stiffness, as can be seen in Fig. 3. For higher stiffnesses however, the power reduction becomes less for frequencies $f < f_{minP}$. More interesting though is the effect of $c_v$ on $f_{minP}$ for both joints. For given stiffnesses one can choose an upper body configuration such that multiple SEA oscillate at their optimum frequency. Fig. 3 shows that the same behaviour is observed for $c_\varphi$. For identical stiffnesses in the knee and hip joint we find that the optimum frequencies for both SEA are identical for approximately $c_v \approx 2.25$ or $c_\varphi \approx 1.25$.

These results highlight interesting possibilities for design and trajectory planning. For a given system set-up, the torque capacities of hip and knee motors might be better exploited by using different upper body configurations, i.e. tilting the body when going downwards. One can use the upper body configuration for choosing differently sized motors in the system or to make all SEA operate at their natural frequencies. For future research it is recommended to look into actual dynamically stable trajectories of the robot, which are not necessarily near-sinusoidal.

[1] Except for very low stiffnesses with very high frequencies (not plotted)

## References


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