

## THE DISTRIBUTION OF WORK BETWEEN ACTIVE AND PASSIVE TISSUES DURING LANDING FROM A JUMP

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### SUMMARY

Mechanical work can be performed by muscles and tendons acting about joints, but also by deformable or wobbling tissues throughout the body. Only muscle can perform net positive work, but active and passive tissues can both perform negative work. This suggests that there is some flexibility in how negative work may be performed, particularly in a task such as jumping where much of the negative work resembles a collision. We hypothesized that humans can modulate the amount of negative work performed by soft tissue deformations vs. muscle when landing from a jump. Subjects performed vertical jumps over a range of heights and with two different styles of landing: (1) Normal and (2) Quiet (instructed to land as quietly as possible, “like ninjas”). We found that for Normal landings from jumps over 20 cm, subjects systematically distributed negative work in roughly constant proportion between active joints (83%) and passive deformable tissues (17%). But Quiet landing was performed with considerably more active joint work, and less passive deformation. This contrasts with the positive work of the jump itself, which was attributable only to muscle. Humans can choose how to dissipate the energy during a collision by modulating the active effort they exert.

### INTRODUCTION

Humans typically have many ways of performing a motor task, but regardless of the joints and muscles used, all of the net positive work must be performed by muscle. The same is not true for negative work, which may be performed actively by muscle or passively through the deformation of non-rigid tissues such as the heel pad, joint cartilage, vertebral discs, and the viscera [1]. In landing from a jump, the magnitude of negative work performed is dictated by jump height. But how that work is distributed between active muscle and passive soft tissues is undetermined. One might choose to perform all of the work actively, but that might require more effort than is desirable. The alternative is to land such that soft tissue deformations absorb most of the energy, but that might be painful or injurious. The choice of work distribution may, therefore, be indicative of the relative costs of pain and effort.

We hypothesized that humans systematically prefer a particular trade-off between these extremes (active joint vs. passive soft tissue work), and that the distribution of negative work can also be altered through conscious choice. To test this hypothesis, we measured how subjects performed a simple jumping task. We estimated each subject’s preferred distribution between work performed by active muscle and

that by passive soft tissues. We also asked subjects to modify how they landed, instructing them to land quietly (“like a ninja”) to test for their ability to modulate that distribution.

### METHODS

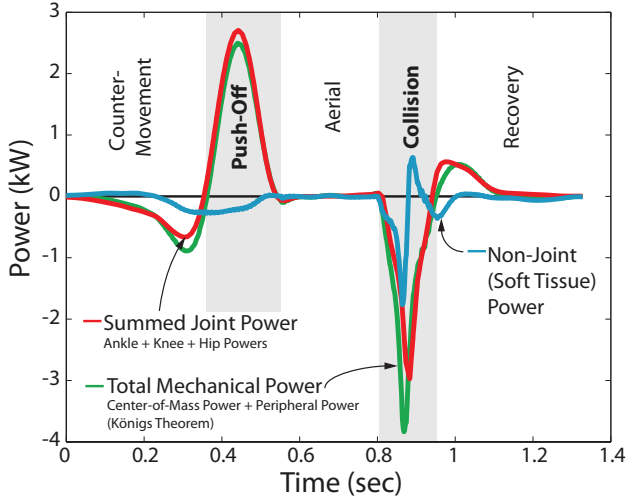
We estimated the work contributions of active muscles vs. passive deformable tissues in jumping and landing. We measured subjects ( $N=8$ ) performing vertical jumping at a range of heights. Trials consisted of standing at rest with arms crossed, jumping vertically, landing and then returning to the original rest position. Subjects performed two types of landings: (1) Normal, in which no landing instructions were given, and (2) Quiet, where subjects were instructed to land as quietly as possible. We estimated joint vs. soft tissue work contributions for different jump heights and for the two different landing styles. Ground reaction forces were collected under each foot with two AMTI force plates. Full-body kinematics were collected with an 8-camera Vicon system.

We used the total mechanical work performed on the body, but not captured by rigid-body joint work estimates as an indicator of soft tissue deformations. We defined Total Mechanical power as that due to motion of the body center-of-mass (COM work rate) plus that due to motion relative to the body COM (Peripheral power), according to Königs Theorem. We computed COM work rate based on the 3D dot product of ground reaction force with COM velocity [2]. Summed Joint power (ankle + knee + hip) for both limbs was computed from conventional inverse dynamics, and used to estimate rigid-body joint work. We divided each jump into phases – Counter-Movement, Push-Off, Aerial, Collision, Recovery – defined by separate regions of positive and negative COM work. We compared Summed Joint power with Total Mechanical power, defining the difference as the Non-Joint (soft tissue) power contribution (Fig. 1). Work summary measures were integrated from power estimates, and these were compared for Push-Off and Collision phases.

### RESULTS AND DISCUSSION

We found that subjects performed work through a combination of joint rotations and soft tissues deformations, with the distribution varying with jump height and landing style. Total Mechanical power exhibited a large positive region of Push-Off before the Aerial phase, followed by a negative region of Collision after landing. Summed Joint power followed a similar pattern, but with timing and magnitude differences due to the work done by soft tissues. Non-Joint power was typically negative during Push-Off and

Collision. During Collision, the region of negative Non-Joint power was often followed by multiple regions of alternating positive and negative power (Fig. 1), suggesting damped-elastic soft tissue deformations.



**Figure 1:** Power vs. time for a representative jumping trial. Non-Joint power, the difference between Total Mechanical and Summed Joint powers, is one indicator of soft tissue deformations.

Most of Push-Off was attributable to active work, with relatively little Non-Joint work (less than 12% of total work, Fig. 2a,b). Non-joint work tended to be negative, indicating that some active joint work may be dissipated in soft tissues. At the highest jump heights, we observed some positive soft tissue work. Because only muscle can perform net positive work this may be due to measurement errors and other inaccuracies, but such errors were less than 10% in all cases.

The magnitudes of joint and soft tissue Collision work increased with jump height (Fig. 2c), but the proportion of the Collision done by joint vs. soft tissues changed. The percentage of Collision work done by soft tissues was highest for low jump heights:  $34 \pm 11\%$  for jump heights of 5 cm (Fig. 2d) and as high as 50-70% for even smaller Collisions with magnitudes comparable to those in walking. At higher jump

heights (greater than 20 cm), the soft tissue contribution plateaued at about 17%. Although the percentage contribution was smaller, soft tissues still performed substantial work, in some cases more than 100 J.

By giving verbal cues to subjects to land as quietly as possible, we were able to alter Collision magnitudes and how negative work was distributed. When performing Quiet landings, soft tissues performed a smaller percentage of the Collision work (Fig. 2d). At the lower jump heights, total Collision work magnitudes were not different from Normal, but more work was performed about the joints. At higher jump heights, the increase in joint work appeared to be primarily from an increase in total Collision work and not from a reduction in magnitude of soft tissue work. We were also able to demonstrate the opposite of Quiet landings by having one subject land stiff and straight-legged. In this case, soft tissues performed as much as 60-80% of the total Collision work.

## CONCLUSIONS

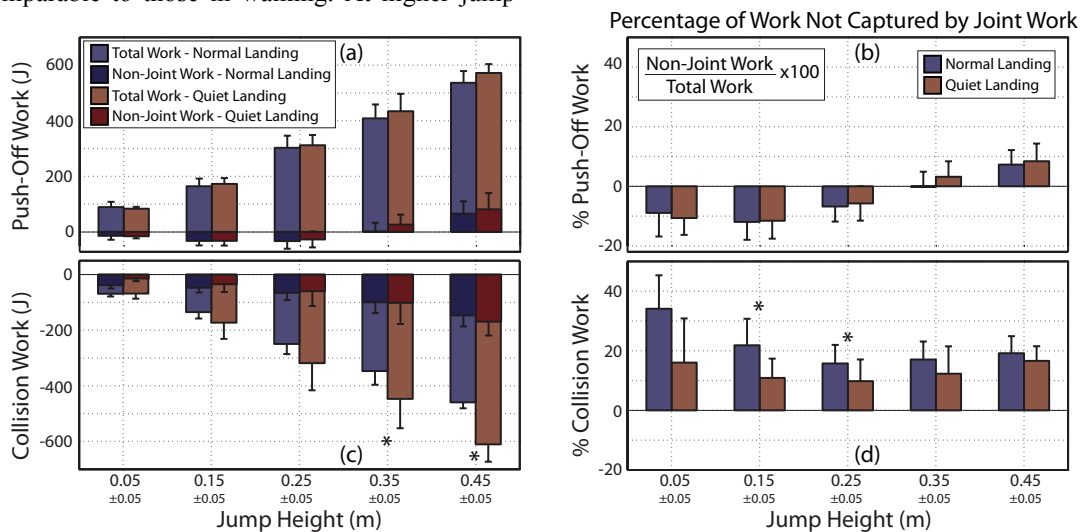
Mechanical work is distributed between active joint rotations and passive soft tissue deformations. Soft tissues perform substantial work during Collisions, increasing with total Collision work. For Collisions similar to those observed in walking, the percentage of Collision work done by soft tissues was highest (50-70%). That proportion decreased with jump height, suggesting that humans are willing to expend more effort for negative muscle work to avoid large amounts of soft tissue work. Perhaps avoidance of pain is worth energy. By instructing subjects to land quietly like a ninja, subjects performed a higher percentage of the Collision work actively.

## ACKNOWLEDGEMENTS

The authors acknowledge the contributions of A.W. Choy and support from the NSF (K.E.Z), the DOD and NIH (A.D.K).

## REFERENCES

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**Figure 2:** Soft Tissue work. Total and Non-Joint (soft tissue) work for (a) Push-Off and (c) Collision. Non-Joint work contributions were small during (b) Push-Off, but accounted for a substantial percentage of the total (d) Collision work, in particular for low jump heights.