Functional Behavior of the Hip Joint Capsular Ligaments During Walking and Running

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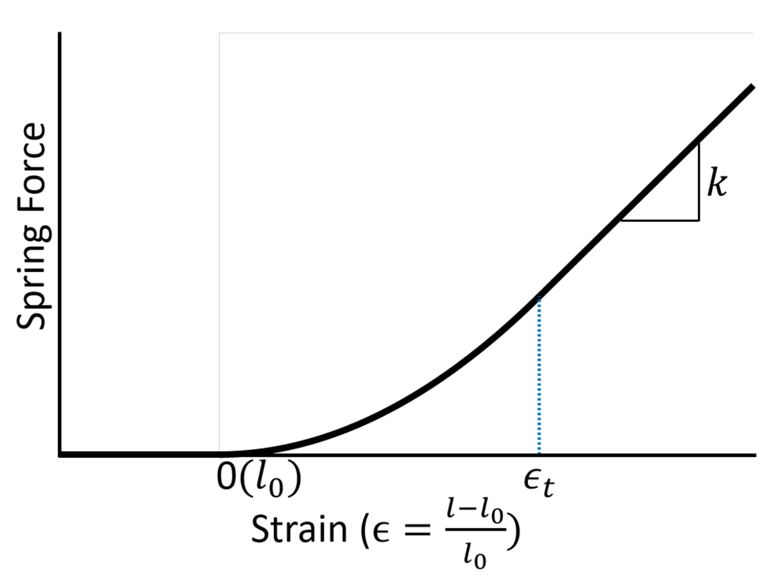
Introduction

Hip capsular ligaments are important for hip joint health and mobility, but their precise dynamics during walking and running are still unknown. This is due in part to their anatomical depth and the presence of surrounding soft tissues, which limit access for direct in-vivo measurements. As such, our understanding of these ligaments is based exclusively on passive, cadaveric manipulations over broad ranges of hip motion and tissue material properties. Here, we use an integrative experimental-modeling approach to estimate the hip ligament strain, force, and power output in walking and running for the first time.

Methods

Three-dimensional (3-D) kinematic data were collected from three male and three female subjects walking and running across a broad range of speeds (1.0–4.0 ms^{-1}) on a level, instrumented force-treadmill. A generic 3-D human musculoskeletal model [1] was modified to include models of the iliofemoral (superior and inferior branches), pubofemoral, and ischiofemoral ligament positions and material properties [4-7]. The generic model was then scaled to each subject's anthropometrics, integrated with experimental 3-D kinematics and used to calculate ligament strain, force and power output at ten different speeds.



$$F_{\text{spring}} = \begin{cases} 0 & \epsilon < 0 \\ \frac{1}{2\epsilon_t} k\epsilon^2 & 0 \le \epsilon \le \epsilon_t \\ k(\epsilon - \frac{\epsilon_t}{2}) & \epsilon > \epsilon_t \end{cases}$$

$$F_{\text{damping}} = \begin{cases} c \cdot \dot{\epsilon} & \epsilon > 0 \text{ and } \dot{\epsilon} > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$F_{\text{total}} = F_{\text{spring}} + F_{\text{damping}}$$

Figure 1. Graphical representation of the force-strain curve applied to gait analysis [2]. Constants and equations are based on measurements of human hip capsular ligament material properties and cross-sectional areas [3].

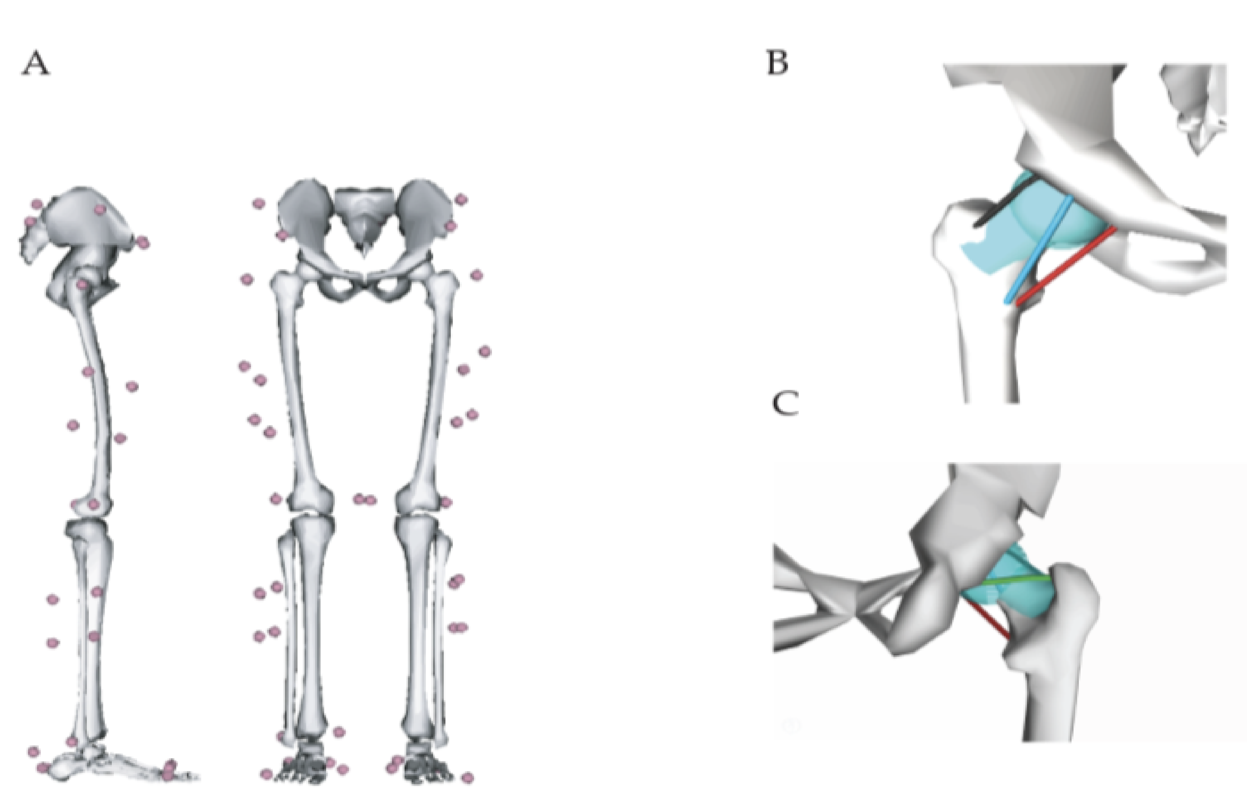


Figure. 2. Models and markers for the human inverse kinematics (A). Pelvis, hip, knee, and ankle are positioned at 0 (i.e., neutral position). Anterior (B) and posterior (C) views of the inferior iliofemoral (blue), superior iliofemoral (black), pubofemoral (red) and ischiofemoral (green) ligaments.

Strain Patterns

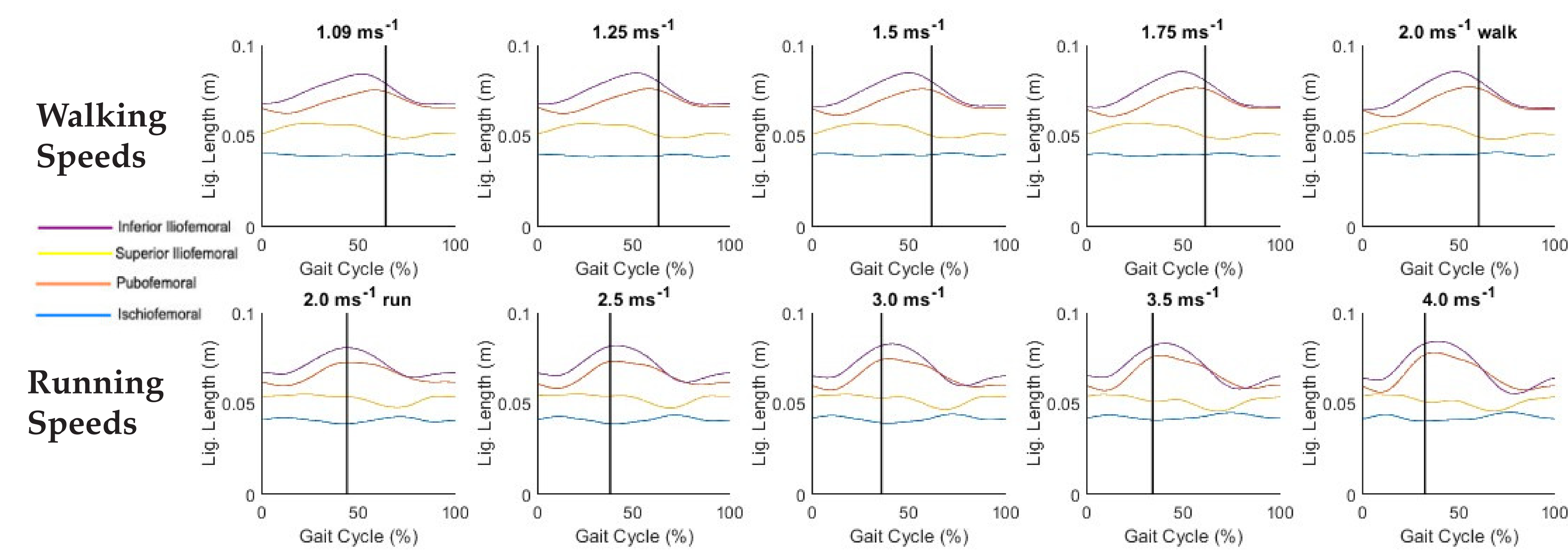


Figure 3. Hip joint ligament strain for five walking speeds ranging from 1.09 ms^{-1} to 2.0 ms^{-1} and five running speeds ranging from 2.0 ms^{-1} to 4.0 ms^{-1}. Plots display the mean values from six subjects, averaged over five strides at each speed. The vertical line indicates the point at which the gait cycle shifts from the stance phase to the swing phase.

Force Patterns

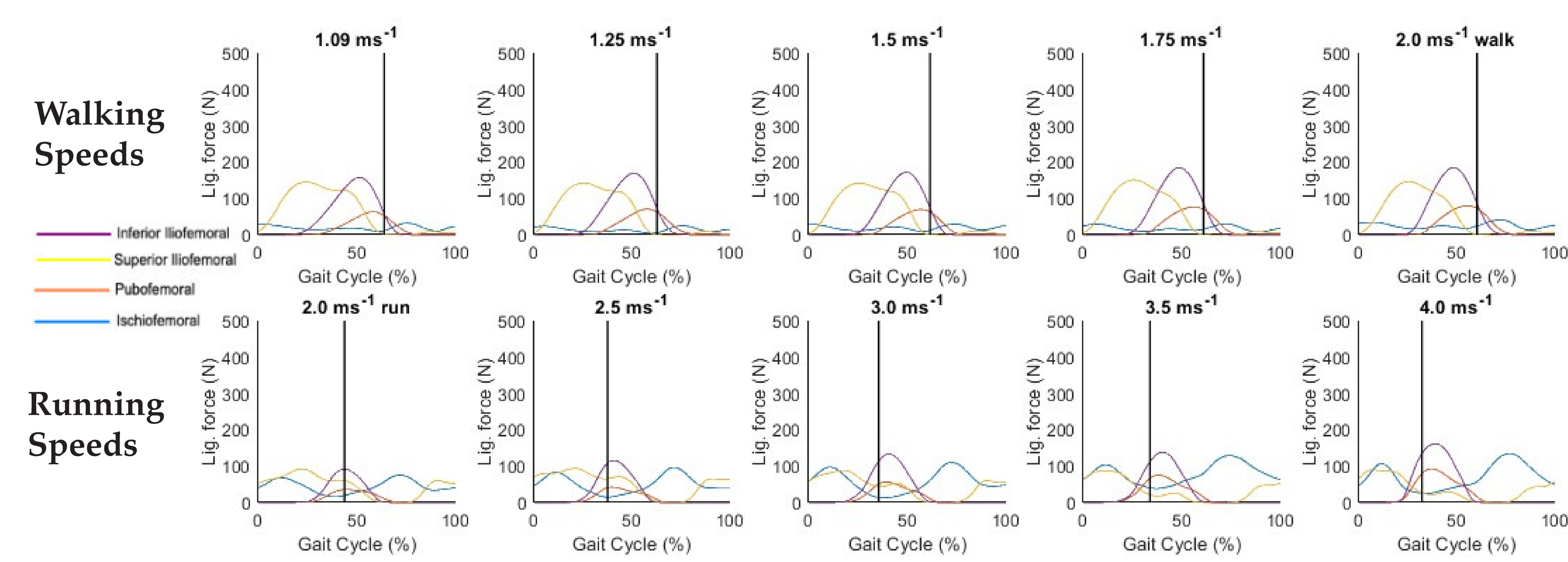


Figure 4. Hip joint ligament force for five walking speeds ranging from 1.09 ms^{-1} to 2.0 ms^{-1} and five running speeds ranging from 2.0 ms^{-1} to 4.0 ms^{-1}. Plots display the mean values from six subjects, averaged over five strides at each speed. The vertical line indicates the point at which the gait cycle shifts from the stance phase to the swing phase.

Power Patterns

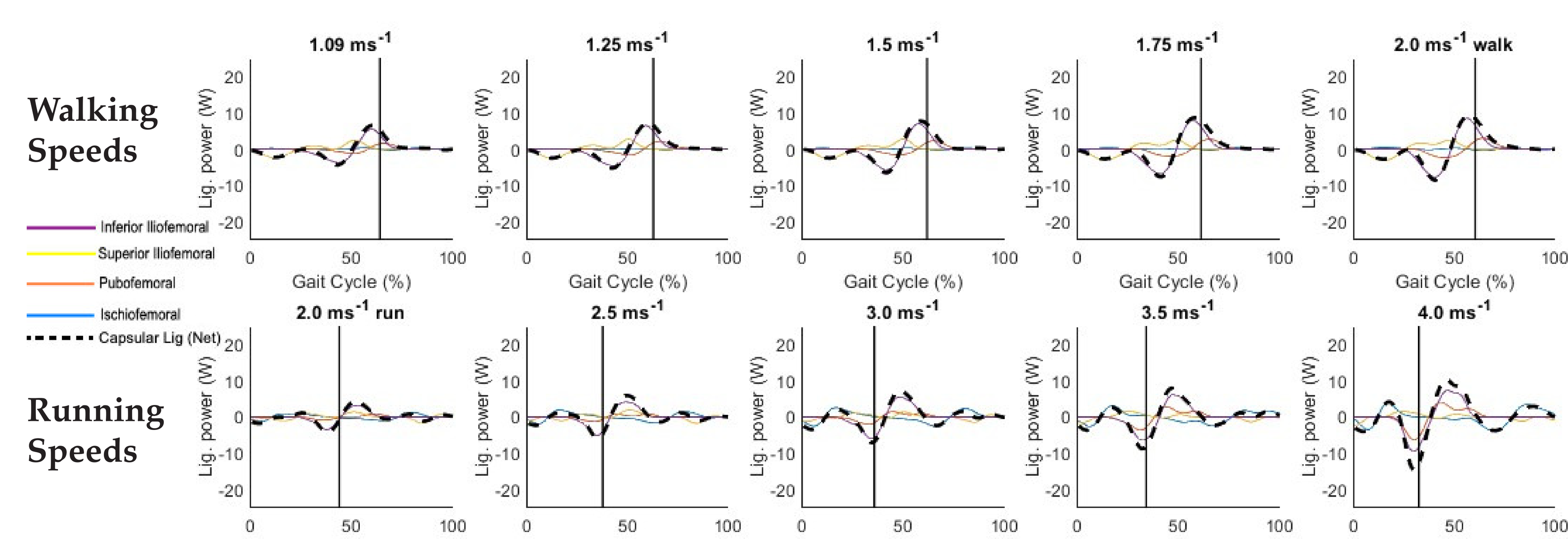


Figure 5. Hip joint ligament power for five walking speeds ranging from 1.09 ms^{-1} to 2.0 ms^{-1} and five running speeds ranging from 2.0 ms^{-1} to 4.0 ms^{-1}. Plots display the mean values from six subjects, averaged over five strides at each speed. The vertical line indicates the point at which the gait cycle shifts from the stance phase to the swing phase.

	Walking Speeds			Running Speeds		
	Peak Strain %	Peak Force N	Peak Power W	Strain %	Force N	Power W
Superior iliofemoral	13	145.0-151.3	2.4-2.5	9	86.9-94.3	1.4-1.9
Inferior iliofemoral	14-16	157.2-184.8	5.4-8.4	9-14	91.6-161.7	3.2-7.3
Pubofemoral	12-15	62.9-79.9	1.6-3.0	8-16	35.5-92.8	0.9-4.1
Ischiofemoral	5-7	24.8-41.2	0.3-0.6	11-17	75.5-135.1	1.2-3.9

Table 1. Mean hip joint ligament peak strain (% of resting length), peak force and peak power output over a walking and running gaits. The values represent ranges from slowest to fastest speeds within each gait.

Results

- The inferior iliofemoral exhibited the highest strain at walking speeds while the ischiofemoral ligament had the highest strain at running speeds.
- The inferior iliofemoral ligament developed the highest force and power output at both walking and running speeds.
- At an equivalent speed of 2.0 m/s, the forces and strains on the hip capsule are higher for walking than running.
- Peak ligament force and positive power occurred at push-off during walking and early swing phase during running. This suggests the hip capsule ligaments make a previously unappreciated elastic

Conclusion

These results provide new data on hip capsular ligament mechanics in human walking and running. The timing and magnitude of ligament strain combined with data on their material properties, suggest that they make a previously underappreciated contribution to storage and relase of elastic power at the human hip in limb push-off during walking and early swing phase during running.

These findings carry important clinical implications for hip arthroscopy. Recent studies show that preserving functional capsular ligaments play a crucial role in hip biomechanics, functional outcomes and hip arthroscopy success rates [8]. The results of this study reinforce and align with these observations.

References and Acknowledgements

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