EFFECTS OF FATIGUE ON THE REGULATION OF LEG SPRING STIFFNESS
Gregory M. Harron¹, Peter F. Vint¹, and Julie A. Kraus²
¹Research Integrations, Inc., Tempe, AZ
²University of North Carolina at Greensboro, Greensboro, NC
E-mail: Greg.Harron@ResearchIntegrations.com

INTRODUCTION
As a greater understanding of the role of leg spring stiffness in locomotion has been realized, research in this area has begun to shift toward the underlying mechanisms that control leg stiffness. Leg stiffness adjustments can be accomplished either by changes in the torsional stiffness of the various leg joints or by changes in the leg geometry at ground contact (Farley & Morgenroth, 1999). Examining the effects of muscle fatigue on leg spring stiffness, leg geometry, and torsional joint stiffness during hopping may help to further explain the role of active muscle force in the regulation of leg spring stiffness.

Landing in a more extended knee position can result in reductions in muscle activity about the knee (Farley et al., 1998). Possible reasons for the decrease in muscle activity include a decreased ground reaction force (GRF) moment about the knee and more force distribution to bone in the landing phase (Farley et al., 1998). Under fatigued conditions, it seems reasonable that a more extended landing position would be implemented to decrease the demands of the active musculature.

Torsional joint stiffness values are dependent upon a number of factors, including muscle activation, reflexes, joint moment, and the angular position of the joint (Farley et al., 1998; Horita et al., 1996). Fatiguing the muscles surrounding a joint may cause changes in any of the above mechanisms involved in joint stiffness regulation.

The purpose of this study was to determine if knee flexor and/or knee extensor muscle fatigue results in changes in hip, knee, and ankle joint stiffness or changes in leg geometry when hopping at a preferred hopping height and frequency.

METHODS
Thirty subjects (mean age 22.6 ± 2.8 years; mean body weight 147.6 ± 29.6 lbs.) were divided evenly into the following three fatigue condition groups: knee extensor fatigue, knee flexor fatigue, and combined knee extensor and knee flexor fatigue. The fatigue protocol consisted of three maximum effort bouts of continuous concentric exertions performed on an isokinetic dynamometer. Each bout was terminated when the subject failed to produce 40% of MVC (maximum voluntary contraction) force for 5 consecutive exertions. All subjects performed two-legged hopping in place at their preferred hopping height and preferred hopping frequency before and after completion of the appropriate fatigue protocol. GRF and sagittal plane kinematic data were collected for all hopping trials at 960 and 60 Hz, respectively.

RESULTS AND DISCUSSION
Across all subjects, the fatigue protocol resulted in a reduction in knee flexion and/or knee extension MVC force of 19.5% following the fatigued hopping trials. However, subjects were able to maintain spring-like characteristics as they hopped. Specifically, for both non-
fatigued and fatigued hoppers, the peak GRF during ground contact typically occurred when the body center of mass was at its lowest point. Subjects maintained similar leg spring stiffness values for pre-fatigued and fatigued hopping trials (Table 1).

The various leg joints maintained torsional spring-like properties with the peak joint moment coinciding with the point of maximal joint flexion under all conditions. There were no significant differences for ankle, knee, or hip joint stiffness values between pre-fatigued and fatigued hopping trials (Table 1).

Limb geometry at landing and at the low point of the ground contact phase was similar for the ankle and knee when comparing pre-fatigued and fatigued hops. The hip joint maintained a slightly more flexed position at landing and at the low point of the hop for fatigued hopping trials. However, the magnitude of these differences was very small (0.030 radians and 0.027 radians for the landing and low point, respectively).

Maximum effort concentric fatigue about the knee presented only small changes in the overall hopping technique. The muscle fatigue protocol may have caused changes to the stiffness of muscle fibers without affecting joint stiffness. Muscle stiffness has been shown to decrease under fatigue (Avela & Komi, 1998), however, the more compliant tendon is typically the limiting factor in the overall combined muscle-tendon stiffness (Alexander, 1997). Therefore, if the fatigued muscles were still able to generate sufficient tension to utilize the elastic properties of the tendon (through near isometric activity for this hopping movement), no major differences in joint stiffness should have resulted. The efficient use of elastic tendon properties in this spring-like movement may have eliminated the need for a major compensatory movement strategy.

REFERENCES

Table 1: Stiffness data for normal and fatigue hopping trials for all groups (mean ± SD).

<table>
<thead>
<tr>
<th></th>
<th>Knee Extensor Group</th>
<th>Knee Flexor Group</th>
<th>Knee Flex/Ext Group</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stiffness</strong></td>
<td><strong>Normal</strong></td>
<td><strong>Fatigue</strong></td>
<td><strong>Normal</strong></td>
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<td>Leg (kN·m⁻¹)</td>
<td>18.8 ± 5.0</td>
<td>18.5 ± 4.9</td>
<td>16.9 ± 4.3</td>
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<td>Ankle (N·m rad⁻¹)</td>
<td>558 ± 196</td>
<td>561 ± 186</td>
<td>491 ± 165</td>
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<tr>
<td>Knee (N·m rad⁻¹)</td>
<td>552 ± 263</td>
<td>584 ± 282</td>
<td>541 ± 174</td>
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<tr>
<td>Hip (N·m rad⁻¹)</td>
<td>84 ± 508</td>
<td>322 ± 554</td>
<td>223 ± 459</td>
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