JOINT-SPECIFIC POWER PRODUCTION, FATIGUE, AND RECOVERY DURING SUBMAXIMAL EXERCISE

Steven Elmer, Justin Grisham, Sara Hahn, and James Martin
Neuromuscular Function Lab, University of Utah, Salt Lake City, UT, USA
Email: steve.elmer@utah.edu

INTRODUCTION
Fatigue during multi-joint tasks may be due to central and/or peripheral mechanisms and could manifest with equal or differential fatigue at each joint. Martin and Brown [6] evaluated changes in joint-specific powers during 30s of maximal cycling during which overall power decreased by 59% and reported differential joint-specific fatigue. An alternative fatigue model involves maintaining a challenging submaximal power output until volitional failure. Interestingly, submaximal cycling is performed mainly with knee extension actions [5] whereas hip extension dominates maximal cycling [6]. In a time-to-failure model, effort required to maintain constant power is initially submaximal and thus may exhibit similar joint-specific power characteristics to submaximal cycling. However, as such a trial progresses, effort will increase, eventually becoming maximal [2]. Our main purpose for conducting this investigation was to quantify alterations in joint-specific power production during multi-joint exercise in a time-to-failure model. We hypothesized that knee extension power would decrease and hip extension power would increase as the effort required to maintain constant power progressed from submaximal to maximal. Our secondary purpose was to determine joint-specific power characteristics following recovery.

METHODS
Nine trained cyclists (31±9y; 73±10kg, 1.76±0.09 m) performed counterweighted single-leg cycling [4] on an isokinetic ergometer (85rpm) at 110% of double-leg lactate threshold power. Participants cycled at this power until volitional failure, after which they rested for 3min and then repeated the effort. Pedal reaction forces were recorded with two 3-component piezoelectric force transducers and pedal and crank position were recorded using digital encoders. Position of the iliac crest was recorded with an instrumented spatial linkage system and limb kinematics were calculated geometrically [7]. Segmental masses, moments of inertia, and locations of centers of mass were estimated using the regression equations reported by de Leva [3]. Sagittal plane joint reaction forces and net joint moments were determined by using inverse dynamic techniques. Joint powers were calculated as the product of net joint moments and joint angular velocities and hip transfer power was calculated as the product of hip joint reaction force and linear velocity. Joint powers were averaged over complete pedal cycles and over extension and flexion phases. Joint powers were analyzed for the initial and final 6s of the first trial and the initial 6s of the second trial. A MANOVA with repeated measures was performed with the measured cycling interval (Trial 1-initial 6s (T1i) vs. Trial 1-final 6s (T1f) vs. Trial 2-initial 6s (T2i) vs. Trial 2-final 6s (T2f)) as the independent variable and ankle plantar flexion, knee extension, knee flexion, and hip extension as dependent variables. If the MANOVA revealed a significant effect of measured interval on joint-specific power values then additional one-way repeated measures ANOVA’s with subsequent post-hoc tests were used to identify which measured intervals were performed with different joint-specific power values. Data are presented as mean±standard error of the mean (alpha=0.05).

RESULTS
Mean power delivered to the pedal did not differ (263±12 vs. 257±10 vs. 265±11W for T1i, T1f, T2i, respectively). The MANOVA revealed a significant effect of measured interval on joint-specific powers (Wilk’s $\lambda=0.21$, F(8,26)=3.87, $p<0.01$). The follow-up ANOVA’s revealed that the effects of measured interval on knee extension, knee flexion, and hip extension powers were significant (F(2, 16)=23.02, $p<0.01$; F(2, 16)=12.05, $p<0.01$; F(2, 16)=11.71, $p<0.01$; respectively). Compared to T1i, knee extension and knee flexion powers during T1f were reduced by 32% and 47%, respectively, whereas hip
extension power increased by 28% (Table 1, Figure 1). Power transferred across the hip increased by 227% (11±12 T1i vs. 25±10W T1f). Joint-specific powers during T1i and T2i did not differ.

DISCUSSION AND CONCLUSION
Our primary finding was that knee extension and flexion powers were reduced as the participants approached volitional failure. These reductions were compensated for with increased hip extension power and hip transfer power so that overall power was maintained. Thus, fatigue during constant submaximal cycling resulted in changes in joint-specific power characteristics. The freedom to select among power producing actions at the ankle, knee, and hip is a benefit of this time-to-failure model in which individuals exploit degrees of freedom to accomplish an overall task goal. Our finding of increased hip extension power prior to failure extends upon recent work by Martin and Brown [6], who reported that hip extension was the dominant power producing action during maximal cycling and was more fatigue resistant than knee extension and flexion actions. We interpret this finding to suggest that differential joint-specific fatigue was due to peripheral rather than central mechanisms. Specifically, muscles that span the ankle, knee, and hip could have different metabolic and morphological characteristics [1]. Our design also included a brief rest period and a second trial to help determine if joint-specific power characteristics were restored following recovery. We found that following a 3min recovery period, joint-specific powers reverted to initial characteristics. This suggests that disturbances to the metabolic milieu were small enough that they could be rapidly restored. These findings have implications for multi-joint endurance, strength, power, and rehabilitation exercises that are performed intermittently until partial or complete fatigue.

Figure 1: Instantaneous power (Mean±SEM) produced by A) knee and B) hip joint actions during submaximal cycling.

REFERENCES

ACKNOWLEDGEMENTS
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Table 1: Power produced during submaximal cycling (Mean±SEM)

<table>
<thead>
<tr>
<th>Cycling Trial</th>
<th>Pedal</th>
<th>Ankle Plantar Flexion</th>
<th>Knee Extension</th>
<th>Kne</th>
<th>Hip Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1 (initial 6s)</td>
<td>263 ± 12</td>
<td>65 ± 10</td>
<td>146 ± 9</td>
<td>79 ± 14</td>
<td>182 ± 20</td>
</tr>
<tr>
<td>Trial 1 (final 6s)</td>
<td>257 ± 10</td>
<td>67 ± 12</td>
<td>100 ± 14a</td>
<td>42 ± 7a</td>
<td>233 ± 23a</td>
</tr>
<tr>
<td>Trial 2 (initial 6s)</td>
<td>265 ± 11</td>
<td>66 ± 10</td>
<td>149 ± 11</td>
<td>71 ± 12a</td>
<td>188 ± 18</td>
</tr>
</tbody>
</table>

a different than Trial 1 (initial 6s)