Conscious Drive to Stiffen the Leg Spring
Motor Strategies for an Internal Challenge

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Abstract: This study investigated the kinematic and muscle activity profiles at the ankle under two hopping conditions that consciously altered leg stiffness. Nine healthy volunteers performed multiple trials of bilateral hopping on a custom built sleigh under two conditions – preferred (PC) and short contact (SC). Leg stiffness, peak EMG, time to peak EMG and co-activation ratios for the medial gastrocnemius (MG), soleus (Sol) and tibialis anterior (TibAnt) muscles were compared across conditions. SC hopping resulted in increased leg stiffness. Importantly, Sol onset shifted from 86ms post-contact during PC to 14ms post-contact for SC. Similarly, MG onset was 41ms post-contact during PC and 22ms pre-contact for SC. Significantly earlier onsets of Sol and MG represent a shift into the feed-forward window which was not reflected by TibAnt. Comparisons revealed no significant differences in co-activation ratios ($p>0.05$) suggesting that increased leg stiffness during SC hopping was not a result of increased co-activation. Instead a dynamic strategy pairing pre-activation with an increased rate of activity of the agonist muscles to develop force in time for contact with the surface was observed. We suggest that the optimal strategy to consciously drive increased leg stiffness occurs via a feedforward response.

1 OBJECTIVES

It is well-established that simultaneous contraction of primary agonist and antagonist muscle groups (i.e. muscle co-activation) will increase the stiffness of a joint (Blickhan, 1989). This process is considered protective, for example when landing (Santello, 2005); (Yeadon et al., 2010). Furthermore, such co-activation has been observed at the knee in athletes following anterior cruciate ligament repair (Bryant et al., 2009) and in the lumbar region in clinical pain cohorts (Hodges et al., 2009); (Morris et al., In Press: 2013); (Moseley et al., 2004); (van Dieën et al., 2003). The common experimental paradigm for investigating stiffness modulation utilises external challenges including hopping and running on surfaces of varying rigidity (Ferris et al., 1999); (Ferris and Farley, 1997); (Moritz et al., 2004), running on uneven surfaces (Müller and Blickhan, 2010) and even reduced cutaneous feedback during hopping (Fiolkowski et al., 2005).

The existing literature does not consider the potential differences in motor strategies responsible for stiffness modulation in response to internal challenges. It cannot be assumed that humans would utilise the same motor strategies to adapt to both internal and external challenges. In fact, a previous study has used conscious effort (an internal challenge) to increase stiffness during hopping by reducing ground contact time (Hobara et al., 2007). Interestingly, they observed increased stiffness without muscle co-activation (Hobara et al., 2007) suggesting that the conscious drive to produce a "stiffer" performance may have its own unique motor strategies. Yet, these specific motor strategies remain unstudied despite being relevant to optimising running performance (Hobara et al., 2010). The specific motor patterns responsible for stiffness modulation under internal challenges are relevant to performance, injury and rehabilitation.

The ankle joint is the major determinant of lower limb stiffness during low load tasks (Farley and Morgenroth, 1999); (Moritz et al., 2004). This study examined the muscle activity profile changes at the ankle associated with consciously driven increase in leg stiffness during repeated submaximal hopping.

Travers M., Debenham J., Gibson W., Campbell A. and Allison G..
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2 METHODS

This study utilised a within-subject experimental design. Nine healthy participants performed multiple hopping trials on a Custom Built Sleigh Apparatus (Figure 1). The sleigh incorporated an instrumented (AMTI forceplate 1kHz sampling) landing platform allowing the establishment of event markers.

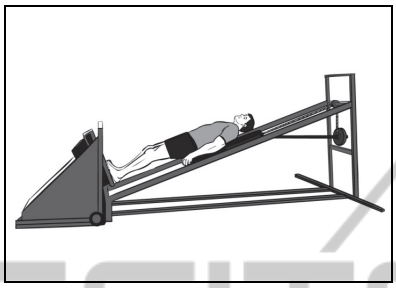

Figure 1: Double leg hopping on the Custom Built Sleigh Apparatus inclined at 20degrees from horizontal.

Each Trial involved 10 continuous bilateral hops on the sleigh apparatus (median 6 used for analysis). Participants minimised any associated knee flexion (no external fixation was used) so that performance was primarily driven by the ankles. Three trials were performed under two different conditions – preferred ground contact time (PC), and with as short a contact time as possible (SC).

Surface EMG for the medial gastrocnemius (MG), soleus (SOL), and the tibialis anterior (TibAnt) muscles was collected using an AMT-8 (Bortec Biomedical Ltd.) system. The EMG signal was full wave rectified and onsets detected using the integrated protocol (Allison, 2003). Trial linear envelopes were created using a fourth-order zero-lag, Butterworth low-pass filter (10 Hz) and temporally synchronised to foot contact. Ensemble average LE were determined for a 760ms window (280ms pre-contact to 480ms post-contact). The feedforward window was defined at 33ms post-contact (Voigt et al., 1998). EMG signals were integrated in 20ms epochs (IEMG) for the 760ms window. The median peak of 10 PC hops was used as a 1.0 arbitrary unit for amplitude normalisation (Allison et al., 1993).

Leg Stiffness (K) was calculated using the formula below (Dalleau et al., 2004):

$$K = \frac{(M \times \Pi(t_f + t_c)}{(t_c^2 ((t_f + t_c / \Pi) - (t_c / 4)))}$$

Figure 2: Formula for estimating leg stiffness (K); M = body mass; tf= flight time; tc = ground contact time.

Co-activation was defined as the ratio of the agonist (MG and Sol) and antagonist (TibAnt) muscle activity and co-activation ratios were labelled MG/TibAnt and Sol/TibAnt.

Paired samples t-tests were used to compare differences in K, co-activation ratios and onset times between conditions. A linear mixed model was utilised to identify any significant difference in onset times for each muscle grouped for condition and side. It was further used to investigate any interaction between condition, side and muscle with onset time as the dependant variable.

3 RESULTS

The participants demonstrated a significant increase in K during SC hopping (Table 1).

Table 1: Leg Stiffness (kN.m-1) by Condition.

Condition	Stiffness (SD)	p
PC	9.20 (2.58)	
SC	14.16 (3.09)*	p <.001

The peak EMG amplitude was not significantly different for any muscle between PC and SC. Further, there was no significant interaction between side and hopping condition (F =.182, p = .671) nor main effects for side (F =.284, p = .596) or condition (F = .690, p = .409).

Sides were pooled for EMG onsets and time to peak EMG as there was no significant interaction between side and muscle or condition ($p > 0.05$).

The Sol onset time was 86ms (95% CI 58ms to 114ms) post-contact for the PC condition and 14ms (95% CI -7ms to 36ms) post-contact for the SC condition (F = 58.145, p <.001). The MG onset time was 41ms (95% CI 25ms to 57ms) post-contact for the PC condition and 22ms (95% CI 35ms to 9ms) post-contact for the SC condition (F = 56.137, p <.001). The TibAnt onset was not altered significantly between conditions (p = .062).

Peak Sol activity occurred at 200ms (95% CI 184ms to 216ms) post-contact for PC and was significantly earlier (p <.001) for SC occurring at 114ms post-contact (95% CI 101ms to 125ms). Similarly, peak MG activity occurred at 195ms post-contact (95% CI 179ms to 211ms) and was significantly earlier (p <.001) for SC occurring at 102ms post-contact (95% CI 91ms to 114ms). The time to peak activity for TibAnt was not significantly different between conditions (p < .05).

Finally, comparisons revealed no significant differences in MG/TibAnt and Sol/TibAnt co-

activation ratios between PC and SC ($p>0.05$).

4 DISCUSSION

Both MG and Sol demonstrated earlier onsets during SC hopping. This represented a change from potential feedback latency to a clear feedforward response with onsets occurring within the defined 33 (+/- 7)ms window (Voigt et al., 1998). Importantly, this was not matched by TibAnt.

Specifically, our findings demonstrate that in the presence of a controlled environment and self-regulation of the pending challenge and consequences (i.e. the choice of hopping contact time on a stable sleigh) individuals may choose a feedforward strategy instead of the established co-activation strategy. We observed a dynamic strategy of pre-activation with an increased rate of activity of the agonist muscle to develop force in time for contact with the surface.

5 CONCLUSIONS

This study investigated the neural control of consciously driven increase in joint stiffness during submaximal hopping. We observed a stiffer hopping performance driven by a feedforward strategy confirming our hypothesis that internal challenges to performance have their own unique motor strategies.

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