8-2022

# Contributions of Vision to the Neuromotor Control and Biomechanics of Depth Jumping

Kenneth Harrison
*Utah State University*

# CONTRIBUTIONS OF VISION TO THE NEUROMOTOR CONTROL AND BIOMECHANICS OF DEPTH JUMPING

by

Kenneth Harrison

A plan B project submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Kinesiology

Approved:

| | |
|---|---|
| Dr. Talin Louder, Ph.D.<br>Major Professor | Dr. Chris Dakin, Ph.D.<br>Committee Member |
| Dr. Anne Beethe, Ph.D.<br>Committee Member | D. Richard Cutler, Ph.D.<br>Interim Vice Provost<br>of Graduate Studies |

UTAH STATE UNIVERSITY
Logan, Utah

2022

## Abstract

**PURPOSE:** To investigate the role of vision during depth jump movements and further explore effects of stroboscopic goggles on the motor control of landing. **METHODS:** Ground reaction force (GRF), rate of force development (RFD), and lower limb surface electromyography measurements were collected on 20 participants (11 male 9 female) across 6 trials of depth jumping (0.51 m) in each of two visual conditions (full vision vs stroboscopic vision). Root-mean-square was estimated from EMG signals that were reduced to specific time-bins (150ms pre touchdown, 30-60ms, 60-85 ms, and 85-120 ms post touchdown). Main effects of and interactions between visual condition and trial number were assessed using repeated measures analysis of variance. **RESULTS:** Peak GRF was 6.4% greater in magnitude on average for DJs performed under condition of stroboscopic vision versus full vision ($p = .042$). There was a significant reduction in Tibialis Anterior activation during the 60-85ms medium latency response window, followed by a significant decrease in activation of the Vastus Lateralus during the 85-120 ms long latency response window. **CONCLUSION:** An influence of controlled visual disruption on depth jump movement performance was observed through altered landing mechanics and lower limb muscle activation patterns. This change presented as increased stiffness achieved before landing followed by larger peak ground reaction forces and subsequent altered muscular response post-landing.

## Introduction

Landing from a fall is a task that requires the human body to generate skeletal muscle force in anticipation of and reaction to large ground reaction forces (GRFs). During a landing impact, GRFs are applied from the ground to the feet, resulting in a distribution of internal stress through the kinetic chain. The magnitude of stress applied to the various structures of the body upon landing may depend on the neural activation of agonist and antagonist skeletal muscle occurring during the fall (Baudry & Duchateau, 2012; Santello et al., 2001). Neural activation leads to an increase in active musculotendinous stiffness prior to landing impact. When humans land from a fall, the muscle-tendon complexes of the lower-extremity must achieve an appropriate level of active stiffness to dampen the energy of impact and partition stress away from fragile joint and skeletal structures (Santello, 2005). Further, when a landing impact is followed immediately by an explosive movement, active stiffness in the muscle-tendon complex is believed to enhance the stretch-shortening cycle (SSC) action of skeletal muscle via several proposed neuromechanical mechanisms (Kamibayashi & Muro, 2006a).

To prepare for and react to GRF expressed at landing impact, musculotendinous stiffness is regulated by a combination of feedforward and feedback motor control (Duysens et al., 2000). Feedforward control relates to the use of environmental ques and learned skills to prepare for the landing via muscle pre-activation and limb positioning (Santello & McDonagh, 1998). Pre-activation is critical to landing successfully since it leads to a “priming” or stiffening of lower extremity joints in anticipation of the timing and magnitude of impact (Duncan & McDonagh, 2000). Enacting a feedforward motor program that contains instructions to develop active muscle tension prior to landing is suggested to be important for distributing stress through the tissues and for controlling joint rotations (Santello, 2005).

Feedback control is responsible for voluntary and involuntary adjustment of muscle activation immediately after touchdown (Duncan & McDonagh, 2000). A principal component of feedback control is the regulation of alpha motor neuron potentiation through physiological interaction between tissue-embedded mechanoreceptors and their spinal reflex pathways. For instance, muscle spindles and Golgi tendon organs are embedded in muscle and tendinous tissue and are sensitive to the change in length and tension placed on the muscle-tendon complex, respectively. During a landing impact, large magnitudes of GRF are applied to the feet with a high rate of force development (RFD), thus the reflexive pathways associated with mechanoreceptor feedback are suggested to play an important role in protecting musculotendinous tissue from excessive stretch and tension as well as in stabilizing the whole-body center of gravity (CoG), controlling joint rotations, and preparing for the performance of a subsequent movement.

There is not a clear dichotomy between the contributions of feedforward and feedback control when landing from a fall (Haeufle et al., 2018). This is largely due to uncertainty regarding the relative role of reflexive and voluntary activation of skeletal muscle (Duncan & McDonagh, 2000). For instance, some have suggested that post landing muscle activity may be a remnant of preprogrammed feedforward control, while others have observed evidence in support of independent reflexive feedback control (Santello, 2005). It is well known that spinal reflex pathways are more rapid than the feedback loops that support voluntary adjustments to muscle activation coming from higher processing centers. Consequently, post-landing EMG signals are commonly divided into response time intervals that can give insight into the relationship between muscle activation, preprogrammed, and reflexive neural input. For instance, short-latency responses are suggested to occur between 30 and 60 ms post-landing, which in most cases would be too quick for a voluntary signal to be created and sent to skeletal muscle in response to the impact forces generated during landing (Duncan & McDonagh, 2000). Further, the time intervals that correspond with medium- and long-latency responses are suggested to be 60-85 ms and 85-120 ms post-landing, respectively, with prior literature revealing that the long-latency response may be influenced by voluntary control (Kurtzer et al., 2008). These time bins provide useful organizational insight into the potential sources of muscle activation, however it should be noted they do not provide a completely clear distinction between preprogrammed and reflexive neural activation.

While stimulation of spinal reflex pathways is largely separate from somatic nervous system activation, it has been noted that the body is able to modulate their sensitivity via descending drive from the CNS (Li et al., 2015). More specifically, the descending drive of alpha motor neurons may work in coordination with gamma motor neurons to maintain muscle spindle sensitivity during concentric and eccentric skeletal muscle actions (Li et al., 2015). This alpha-gamma co-activation is suggested to be important for maintaining proportionality between joint position and Ia afferent signaling in other mammals such as cats (Li et al., 2015) which, in turn, facilitates subtle control of movement and posture via the muscle spindle. Further, it is suggested that descending drive may encode centrally planned instructions in both alpha and gamma motor neurons (Li et al., 2015), leading to the possibility that muscle spindle sensitivity in humans is modulated in anticipation of an incoming joint rotation or muscle stretch (Kamibayashi & Muro, 2006; Santello & McDonagh, 1998).

Common across both feedforward and feedback control pathways is the utilization of sensory information for improving the accuracy of motor output (Helm, M., Ritzmann, R., Gollhofer, A., & Freyler, K.2019). Sensory afferents synapse at varying levels of the somatic and autonomic nervous system and are consolidated in the CNS by structures of the brain through a process known as multisensory integration. Multisensory integration involves the CNS weighting visual, vestibular, and proprioceptive inputs to organize, decipher, and interpret relevant characteristics of the internal and surrounding environment prior to the formation of a proper motor response. During a fall, multisensory integration may play a role in fine-tuning the feedforward landing program prior to impact (Haeufle et al., 2018).

There has been recent interest in exposing the role of continuous visual input on the motor control of landing impacts since CNS interpretation of where the body is and how it is moving in relation to the environment is heavily dependent on visual ques (Nashner & Berthoz, 1978). Researchers often use a 'free-fall' paradigm to investigate the contribution of vision to the motor control of landing impacts (Liebermann & Goodman, 2007). This paradigm involves the performance of a task meant to mimic functional movements like stepping downstairs and landing from a jump or cutting movement in sport. Drop landings and depth jumps (DJs) are common movements used to employ the paradigm, with both involving a self-initiated drop from a raised platform onto a landing pad (Liebermann & Goodman, 2007). Upon landing impact, drop landings involve stabilization of the body in a standing static pose whereas DJs involve a quick absorption of landing impact followed immediately by the performance of a maximal vertical jump. Consequently, drop landings provide more insight into neuromuscular patterns relating to the absorption and stabilization of GRFs post-landing, whereas the DJ permits exploration of lower-extremity SSC ability since performance is enhanced by one's capacity to store and recapture the energy of landing impact in support of producing a forceful and explosive movement immediately after landing.

There is prior evidence that vision plays a role in the motor control of DJ, with the restriction or modulation of visual input having a measurable effect on joint kinematics (Kroll, M., Preuss, J., Ness, B. M., Dolny, M., & Louder, T., 2020), landing kinetics (Kamibayashi & Muro, 2006), and EMG pre-activation patterns during both the drop and landing phases (Helm et al., 2019). Most commonly, researchers use a blindfold to remove continuous visual input during the performance of DJ, giving binary conditions wherein the jump is performed either with or without vision. CNS integration of visual input is dynamic, with the reliability of vision being dependent on a multitude of factors ( Shenton, J. T., Schwoebel, J., & Coslett, H. B., 2004b). Stroboscopic eyewear are a practical technology for controlled visual disruption that can be used outside of a lab setting, giving the potential for expanding the scope of investigation into the influence of continuous visual input on the motor control of DJ. Stroboscopic eyewear provides controlled visual disruption through oscillation of the lenses between defined time periods of opacity and transparency, with the frequency of oscillation corresponding to the ‘intensity’ of sensory deprivation (Kroll et al., 2020). It is suggested that stroboscopic vision may lead to a compensatory strategy in the brain where lack of vision up-regulates the use of other sensory information to perform the desired task, also known as sensory reweighting. (Kim, K. M., Kim, J.-S., Oh, J., & Grooms, D. R., 2020a). Recently, Kroll et al. (2020) observed a significant reduction in DJ performance when participants performed jumps under condition of stroboscopic vision versus full vision. In this investigation, DJs were evaluated using the reactive strength index (RSI), which is a broad metric of performance. Considering that Kroll et al. (2020) did not include measures of EMG, there is a need for a more comprehensive investigation into the effects of stroboscopic vision on DJ performance.

The purpose of this study was to evaluate for acute effects of stroboscopic vision on the feedforward and feedback control of DJ. It was hypothesized performing the DJ under condition of stroboscopic vision will increase the uncertainty of landing impact prediction, leading to a decrease in lower limb muscle pre-activation magnitude (e.g. lower stiffness). It was also hypothesized that post-landing EMG magnitude corresponding with the short-, medium-, and long-latency responses would be reduced when DJs were performed under condition of stroboscopic vision. Since short latency responses (30-60ms) occur too rapidly to be influenced by voluntary control, they may be most reliant upon the musculotendinous stiffness achieved pre-landing. Consequently, it was expected that the smallest effect of stroboscopic vision would correspond with the long-latency (85-120ms post-landing) response and the largest effect with the short-latency response. Lastly, it was hypothesized that alterations in EMG activation would be expressed through observed difference in landing impact kinetics. Specifically, it was hypothesized that peak ground reaction force (GRF) and rate of force development (RFD) would increase as stroboscopic vision may lead to a reduced ability to optimize leg stiffness upon landing.

## Methods

### Participants

Twenty male and female young adults volunteered to participate in this study (Table 1). To be eligible, participants: (a) had to be between 18 and 35 years of age and (b) self-reported as physically active such that they engaged in a minimum of 90 minutes per week of moderate to vigorous intensity exercise as part of their normal leisure time. Participants' physical activity routine needed to include jumping, running, and/or sprinting movements. Participants were excluded from the study if: (a) they reported current physical discomfort or an injury that would have affected their ability to jump, (b) reported having a surgical intervention on the lower limbs or trunk in the prior 2 years, (c) reported having sustained an ACL or lower-extremity ligament injury in the past, (d) they reported having had corrective eye surgery in the past year, (e) they reported having been diagnosed with a visual impairment that cannot be corrected by refraction (e.g. contacts/glasses), (f) they reported a history of concussion or seizure. Participants were required to provide written consent on an informed consent document approved by the University Institutional Review Board.

Table 1. Participant characteristics.

| Sex | n | Age (years) | Height (cm) | Body Mass (kg) |
|---|---|---|---|---|
| Female | 9 | 21.8 (1.7) | 166.6 (4.3) | 62.8 (6.6) |
| Male | 11 | 22.9 (1.8) | 179.4 (7.4) | 80.9 (8.5) |

Data are reported as mean (SD).

**Procedures**

Participants were asked to attend a Human Performance Laboratory for two separate testing sessions. Testing sessions were scheduled 48 hours apart to allow adequate recovery time. Participants were asked to refrain from participating in vigorous exercise (e.g. resistance training) 48 hours prior to the first visit through the completion of the study procedures.

During the first visit, participants underwent a familiarization of study procedures. Participants then completed a 10-minute warm-up involving a 5-min bout of stationary cycling followed by a standard jumping warm-up per the National Strength and Conditioning

Association (NSCA). Participants then rested for 3 minutes followed by practice performing the DJ movement under condition of full vision. DJs were performed by having participants step forward from a platform raised 0.51 m above the laboratory floor. Participants self-initiated the drop from the platform immediately after receiving the following standard verbal que: "Step forward from the platform with your preferred foot. Land from the drop with both feet impacting the ground at the same time". Participants landed with both feet impacting a tri-axial force platform (Model FP4080, Bertec Corporation, Columbus, OH, USA) that is recessed to be flush with the laboratory floor and positioned 0.30 m in front of the dropping platform. Upon landing they were instructed to perform a maximal jump upwards as "quickly and as high as possible". For each trial of DJ, participants were instructed to focus their visual gaze on a marker placed at 0.30 m in front of the force platform. Participants arm motion was not restricted, which will facilitate a jumping technique that better represents the performance of jumping and landing in real-world settings. After receiving a visual demonstration of the DJ technique, participants performed a minimum of 10 practice trials of DJ under condition of full vision. All practice trials were monitored by a member of the research team, with augmented feedback provided if necessary.

For the second visit, participants were asked to wear athletic attire that permits skin exposure of the lower half of the thigh (e.g. gym shorts). Participants then completed the same 10-minute warm-up performed in the familiarization session, which was then followed by a 10-minute rest period. During the rest period, wireless surface electromyography (EMG) electrodes (Mini Wave Infinity, Cometa, Milan, Italy) were placed over the tibialis anterior (TA), medial gastrocnemius (GM), vastus lateralis (VL), vastus medialis (VM), and biceps femoris (BF) of the leading leg. Electrodes were located and attached in accordance with standard recommendations provided by the SENIAM (Surface EMG for Non-Invasive Assessment of Muscles; seniam.org) project. Following the rest period, participants completed a study protocol consisting of 6 successful DJ trials performed under condition of full vision (control) and stroboscopic vision (experimental). The order of conditions was counterbalanced, with all trials performed in each condition prior to advancing to the subsequent condition. DJ trials were performed using procedures consistent with the familiarization session. All trials were monitored visually by a member of the research team. Successful trial criteria included landing with both feet at the same time and performing a maximal jump upwards upon landing with minimal delay (ground contact time).

## Data Analysis

### *Data Acquisition*

Vertical GRF data was acquired from the tri-axial force platform (1000 Hz). EMG data was acquired from each of the surface electrodes (2000 Hz). Digital time-series signals for GRF and EMG data were time-synched and captured within the Vicon Nexus (Version 2.12, Vicon Motion Systems Ltd., Oxford, UK) software platform.

### *Data Processing*

GRF and EMG signals were exported from Vicon Nexus and processed in Matlab (Version R2021a, The Mathworks Inc., Natick, MA, USA). GRF signals were passed through a low-pass 4th order, recursive Butterworth filter (300Hz cut-off frequency). GRF signals were then pared to begin at the time instant of landing impact using methods described previously (Louder, Thompson, Banks, & Bressel, 2019). EMG signals were passed through a band-pass 4th order, recursive Butterworth filter (10-500 Hz).

### *GRF Measures*

Peak GRF was defined as the maximum value from pared GRF data. Rate of GRF development (RFD) was defined as the ratio of peak GRF to the time interval between DJ landing impact and the expression of peak GRF. Peak force reduction (PFR) was defined as the difference between peak GRF and the first successive local minimum GRF value. Peak GRF, RFD, and PFR were normalized to body weight (BW; (Mullineaux et al., 2006).

### *EMG Measures*

***Pre-activation***. For each skeletal muscle, the magnitude of pre-activation during the drop phase was defined as the root mean square (RMS) of each EMG signal corresponding to a time duration of 150 ms prior to landing impact (Santello & McDonagh, 1998).

***Landing Impact***. For each skeletal muscle, EMG signals were divided into three time intervals: Short-latency response (SLR, 30-60ms post-landing impact), medium-latency response (MLR, 60-85ms post-landing impact), and long-latency response (LLR, 85-120ms post-landing impact). The timing of the SLR, MLR, and LLR is based on recommendations from prior literature (Helm et al., 2019). The magnitude of skeletal muscle activation during the short-, medium-, and long-latency intervals was defined as the RMS of each EMG signal corresponding to the time duration of the SLR, MLR, and LLR.

## Statistical Analysis

An a priori power analysis in G*Power (version 3.1) was performed using published GRF data acquired from female NCAA Division I volleyball athletes who performed DJs under condition of full vision and stroboscopic vision (Kroll et al., 2020). The power analysis indicated that a sample of 6 participants would give sufficient power for measures of peak landing GRF and RFD. The normality of dependent measures was evaluated using the Shapiro-Wilks test for normality. The inter-trial reliability of all dependent measures was evaluated using intraclass correlation coefficient (ICC) estimates and their 95% confidence intervals (95% CI) based on a single measure, absolute agreement, 2-way mixed effects model. Interpretation of ICC estimates was based on recommendations from Koo & Li (2016). Values less than 0.5 are indicative of poor reliability, values between 0.5 and 0.75 indicate moderate reliability, values between 0.75 and 0.9 indicate good reliability, and values greater than 0.90 indicate excellent reliability. For all dependent measures, main effects and interactions between visual condition (full vision × stroboscopic vision) and DJ trial number (Trial 1 × Trial 2 × Trial 3 × Trial 4 × Trial 5 × Trial 6) were evaluated using a 2-way within-subjects repeated measures Analysis of Variance (RMANOVA). Upon observation of a visual condition × trial number interaction, post-hoc analysis was performed using a one-way RMANOVA followed with paired *t*-tests to evaluate for main effects and statistical significance of visual condition on trial number. Upon the observation of main effects of visual condition, post-hoc analysis was performed using paired *t*-tests. All statistical analyses were performed in RStudio (Version 1.1.456). Upon the observation of a main effect of trial number, post-hoc analysis was performed using Bonferroni-adjusted paired *t*-tests. All hypothesis tests were conducted using an alpha type I error threshold of $p < 0.05$ to make determinations of statistical significance.

## Results

### Reliability

Results on the inter-trial reliability of GRF and EMG measures are presented in Tables 2 and 3, respectively.

Table 2. Inter-trial reliability of kinetic data.

| Measure | Full Vision | Stroboscopic Vision |
|---|---|---|
| Peak GRF | 0.637 (0.456-0.808) | 0.478 (0.286-0.697) |
| RFD | 0.587 (0.401-0.775) | 0.643 (0.465-0.812) |
| PFR | 0.619 (0.436-0.797) | 0.696 (0.530-0.844) |

Data are presented as ICC estimate (95% confidence interval). GRF = ground reaction force; RFD = rate of force development; PFR = peak force reduction.

Table 3. Inter-trial reliability of muscle activity.

| Measure | | Full Vision | Stroboscopic Vision |
|---|---|---|---|
| Pre | VM | 0.850 (0.744-0.929) | 0.840 (0.728-0.924) |
| | VL | 0.798 (0.667-0.902) | 0.942 (0.895-0.974) |
| | BF | 0.611 (0.428-0.791) | 0.777 (0.636-0.891) |
| | TA | 0.768 (0.625-0.886) | 0.826 (0.708-0.917) |
| | GM | 0.791 (0.656-0.898) | 0.836 (0.722-0.922) |
| SLR | VM | 0.826 (0.708-0.917) | 0.790 (0.655-0.897) |
| | VL | 0.705 (0.541-0.849) | 0.868 (0.772-0.938) |
| | BF | 0.836 (0.723-0.922) | 0.692 (0.524-0.842) |
| | TA | 0.388 (0.202-0.624) | 0.442 (0.252-0.688) |
| | GM | 0.693 (0.461-0.809) | 0.406 (0.220-0.638) |
| MLR | VM | 0.643 (0.465-0.812) | 0.666 (0.493-0.826) |
| | VL | 0.784 (0.647-0.894) | 0.657 (0.482-0.820) |
| | BF | 0.844 (0.736-0.926) | 0.907 (0.835-0.957) |
| | TA | 0.507 (0.318-0.718) | 0.505 (0.314-0.718) |
| | GM | 0.666 (0.493-0.826) | 0.621 (0.440-0.798) |
| LLR | VM | 0.686 (0.517-0.839) | 0.693 (0.527-0.843) |
| | VL | 0.772 (0.630-0.888) | 0.736 (0.582-0.867) |
| | BF | 0.882 (0.794-0.945) | 0.899 (0.822-0.954) |
| | TA | 0.575 (0.388-0.767) | 0.359 (0.177-0.598) |
| | GM | 0.718 (0.559-0.857) | 0.608 (0.425-0.789) |

Data are presented as ICC estimate (95% confidence interval). Pre = pre-activation; SLR = short-latency response; MLR = medium-latency response; LLR = long-latency response; VM = vastus medialis; VL = vastus lateralis; BF = biceps femoris; TA = tibialis anterior; GM = medial gastrocnemius.

**ANOVA**

A main effect of visual condition was observed for peak GRF ($F = 4.5$, $p = 0.035$). Post-hoc analysis revealed that peak GRF was significantly greater for DJs performed under condition of stroboscopic vision versus full vision ($p = 0.042$; Table 4). No main effects of visual condition were observed for RFD ($F = 0.6$, $p = 0.439$) and PFR ($F = 1.7$, $p = 0.188$). There were no main effects of trial number on GRF measures ($F = 0.2 – 1.6$; $p = 0.152 – 0.978$).

Table 4. Central tendency and dispersion for GRF measures.

| Measure | Full Vision | Stroboscopic Vision |
|---|---|---|
| Peak GRF (BW) | 4.66 (1.26) | 4.96 (1.64)* |
| RFD ($BW*s^{-1}$) | 94.27 (49.74) | 97.34 (43.72) |
| PFR (BW) | 2.28 (1.22) | 2.42 (1.44) |

*Significantly different from full vision ($p < 0.05$). GRF = ground reaction force; RFD = rate of vertical ground reaction force development; PFR = peak ground reaction force reduction.

There was a significant visual condition × trial number interaction on VM MLR ($F = 2.4$, $p = 0.037$). Post-hoc analysis revealed that VM MLR under condition of full vision was significantly greater than under condition of stroboscopic vision for trial number 1 ($p = 0.043$; Figure 1). There was no other significant visual condition × trial number interactions on EMG ($F = 0.2 – 1.8$; $p = 0.106 – 0.944$) or GRF ($F = 0.4 – 0.8$; $p = 0.534 – 0.860$) measures.

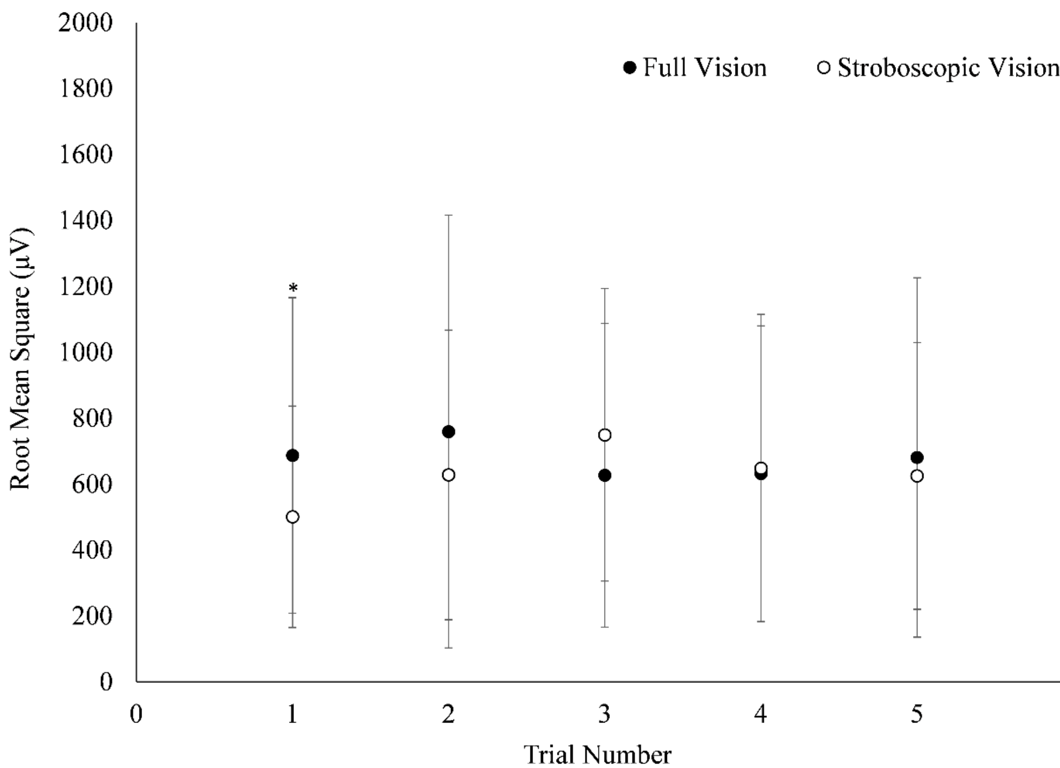


Figure 1. Visual condition × trial number interaction on vastus medialis medium-latency response.

No main effect of visual condition was observed for pre-activation magnitude (*F* = 0.0-3.0, *p* = 0.087-0.902), however, the main effect of visual condition on VL pre-activation magnitude approached statistical significance (*F* = 3.0, *p* = 0.087; Table 5). There was a main effect of trial number on BF pre-activation magnitude (*F* = 3.1, *p* = 0.009), however, post-hoc analysis using a Bonferroni-adjusted alpha level of 0.003 revealed no significant differences between trials (*p* = 0.010-0.994). There were no other main effects of trial number on EMG pre-activation magnitude (*F* = 0.5-1.2, *p* = 0.298-0.807).

There were no main effects of visual condition (*F* = 0.0-2.5, *p* = 0.117-0.914) or trial number (*F* = 0.6-1.3, *p* = 0.281-0.675) on SLR EMG magnitudes. There was a main effect of visual condition on TA MLR magnitude (*F* = 5.6, *p* = 0.020). Post-hoc analysis revealed that TA

MLR magnitude was reduced for DJs performed under condition of stroboscopic vision ($p$ = 0.014; Table 5). No other main effects of visual condition were observed for MLR magnitude ($F$ = 0.1-1.0, $p$ = 0.319-0.778), however, the main effect of visual condition on BF MLR approached statistical significance ($F$ = 3.0, $p$ = 0.083; Table 5). No main effects of trial number were observed for MLR magnitude ($F$ = 0.7-1.7, $p$ = 0.142-0.632). There was a main effect of visual condition on VL LLR magnitude ($F$ = 5.8, $p$ = 0.017). Post-hoc analysis revealed that VL LLR magnitude was reduced for DJs performed under condition of stroboscopic vision ($p$ = 0.030; Table 5). No other main effects of visual condition were observed for LLR magnitude ($F$ = 0.4-1.6, $p$ = 0.206-0.542), however, the main effects of visual condition on VM LLR ($F$ = 3.2, $p$ = 0.075) and BF LLR ($F$ = 3.1, $p$ = 0.079) approached statistical significance (Table 5).

Table 5. Central tendency and dispersion for RMS EMG measures.

| Measure | Muscle | Full Vision | Stroboscopic Vision |
|---|---|---|---|
| Pre (μV) | VM | 376.76 (302.92) | 379.30 (340.75) |
| | VL | 305.29 (291.25) | 334.17 (369.66)$^{¥}$ |
| | BF | 139.32 (198.07) | 147.60 (207.89) |
| | TA | 242.79 (123.46) | 241.34 (145.00) |
| | GM | 225.11 (114.82) | 225.94 (114.77) |
| SLR (μV) | VM | 846.16 (630.22) | 865.76 (650.52) |
| | VL | 613.22 (417.14) | 602.75 (485.01) |
| | BF | 336.75 (487.07) | 393.72 (533.15) |
| | TA | 435.93 (250.43) | 438.72 (233.69) |
| | GM | 172.12 (153.19) | 157.65 (144.89) |
| MLR (μV) | VM | 663.08 (489.32) | 654.20 (445.49) |
| | VL | 522.50 (364.44) | 553.93 (467.56) |
| | BF | 333.83 (604.82) | 387.26 (668.96) $^{¥}$ |
| | TA | 455.44 (306.97) | 391.18 (271.92)* |
| | GM | 184.53 (200.94) | 179.99 (208.28) |
| LLR (μV) | VM | 673.24 (489.39) | 610.51 (430.71) $^{¥}$ |
| | VL | 518.23 (402.95) | 457.05 (359.28)* |
| | BF | 271.64 (520.39) | 323.03 (669.96) $^{¥}$ |
| | TA | 359.53 (279.72) | 341.96 (299.31) |
| | GM | 189.39 (208.99) | 212.81 (265.58) |

*Significantly different from full vision ($p < 0.05$). $^{¥}$Approached significance ($p < 0.10$). RMS = root mean square; EMG = surface electromyography; Pre = pre-activation; SLR = short-latency response; MLR = medium-latency response; LLR = long-latency response; VM = vastus medialis; VL = vastus lateralis; BF = biceps femoris; TA = tibialis anterior; GM = medial gastrocnemius.

## Discussion

The purpose of this study was to investigate the contribution of online vision to DJ performance to better understand sensory integration from the perspective of feedforward and feedback motor control. Participants performed 6 trials of DJ under condition of full vision and 6 trials under condition of 3 Hz stroboscopic vision. The inter-trial reliability of dependent measures estimated from GRF and EMG data ranged from poor to excellent. Thus, dependent measures were averaged across 6 trials for each visual condition to mitigate the influence of inter-trial variability on statistical findings.

Peak GRF was observed to be 6.4% greater in magnitude, on average, for DJs performed under condition of stroboscopic vision versus full vision. This finding, when paired with no observed change in RFD, suggests that the post-landing time to expression of peak GRF was longer in duration. The observed delay in achieving peak GRF for the experimental condition may be interpreted as an increase in the time taken for the body to begin controlling its downwards momentum post-touchdown via distribution of forces across musculoskeletal structures. Such a difference could also reflect the development of a mismatch between limb stiffness achieved pre-touchdown and landing impact momentum due to insufficient visual data available for central processing.

Lower limb stiffness is important during landing movements to direct the application of vertical forces away from fragile structures towards skeletal muscle as well as for explosive movements such as the DJ in priming tissue for effective use of the SSC. Stiffness provides resistance to compression resulting from the dynamic coordination of muscles and joints throughout the entire involved kinetic chain (Hughes & Watkins, 2008). Previous studies have shown higher magnitudes of stiffness to be associated with increased peak GRF achieved during landing (Shih et al., 2019). Vertical stiffness was not estimated in the present investigation yet increased peak GRF is suggestive of a potential increase in stiffness for DJs performed under condition of stroboscopic vision. It could be postulated based on these findings that visual afferents might be important for controlling the feedforward planning and optimization of limb stiffness during landing movements. When vision is restricted, the limbs may not reach an effective level of stiffness during landing resulting in the observed increase in peak GRF.

VL pre-activation EMG magnitude increased by 9.5%, on average, for DJs performed under condition of stroboscopic vision, a result that approached statistical significance. This finding suggests that participants expressed a tendency to pre-emptively stiffen the knee when DJs were performed with restricted vision, potentially as a protective strategy to compensate for less sensory information as well as a miscalculation of landing impact timing. The former explanation is consistent with the interpretation that increased peak GRF during DJ landing could potentially be explained by an increase in limb stiffness resulting from the intermittent removal of vision. This is also supported by Helm et al. (2019) who observed that anticipation of ground forces associated with different landing surfaces can influence joint stiffening prior to impact. It is possible that stroboscopic vision elicited neural activation indicative of a lack of confidence in the landing surface and a precautionary feedforward motor program was put forward, leading to preparatory adjustments in knee activation prior to landing.

Since RMS muscle activation magnitudes were estimated using preselected temporal bins, it is also possible that the trend of increased VL pre-activation magnitude was a result of the CNS misjudging the timing of landing impact with the ground. There is some evidence that vision can be functionally replaced in specific tasks by upweighting other sensory or learned timing information to support the judgement of fall height (Santello, 2005). This estimation of fall height helps the motor control system determine when to initiate pre-activation before ground contact (Santello, 2005). Pre-landing EMG onset timing has been observed to remain unchanged regardless of falling height (Galindo et al., 2009), which suggests that the motor control system adjusts pre-activation magnitude, rather than duration, in response to the perception of the magnitude of landing impact momentum. Given that the present investigation involved participants performing the DJ from a consistent box height with a landing surface that was visible across both the control and experimental conditions, it can be assumed that stroboscopic vision likely influenced pre-activation magnitude to a greater extent than participants' estimation of when to initiate pre-activation.

After touchdown, there was a statistically significant 14.1% reduction in TA activation during the MLR, on average. While this result may be explained by reciprocal inhibition from increased potentiation of muscle spindles in the ankle extensors, we did not observe a concomitant increase in GM activation post-landing. It is suggested that muscle spindle feedback is more prominent in the soleus compared to the more superficial GM (Tucker & Türker, 2009). Thus, activation of the soleus stretch reflex during touchdown could be responsible for eliciting a spinal reflex arc resulting in inhibition of the TA, which would facilitate an increase in net joint torque towards plantarflexion. Prior evidence supports the notion that a reduction in TA activation magnitude could be a result of muscle spindle potentiation in the plantar flexors. For instance, Duncan & McDonagh (2000) observed post-landing EMG activity of the plantar flexors to be significantly reduced under condition of falling through an unexpected false floor in comparison with landing on a true floor. This suggests that post-landing EMG activation in the ankle is partially the result of load-dependent receptors such as muscle spindles which would explain our observed inhibition of dorsiflexors.

After touchdown, there was also a significant 11.8% reduction in VL activation during the LLR, on average, which occurred concomitantly with an average reduction of 9.3% in VM activation during the LLR that approached statistical significance. Notably, the trend toward decreased knee extensor activation during the LLR was accompanied by a 16% and 18.9% average increase in BF activation magnitude during the MLR and LLR, respectively. Although the increases in BF activation magnitude were findings that approached statistical significance, collectively the results are suggestive that DJs performed with stroboscopic vision involve a greater hamstring to quad activation ratio elicited post-landing. Additional analysis may confirm this supposition, which would reflect a decrease in knee torque towards extension. Such a decrease would infer a softer landing impact through the knee with a greater proportion of stress possibly absorbed through either the hip or ankle joints.

From the results of the present investigation, it is difficult to decipher the role of vision in the feedforward and feedback control of the DJ. The trend toward increased VL pre-activation suggests that vision likely influences feedforward muscle activation specific to the optimization of limb stiffness in anticipation of landing impact. Thus, the intermittent removal of online vision may be a modulator of muscle pre-activation due to a change in sensory feedback, however it is unclear whether this change was in the feedforward instructions prior to the drop or rather were modifications to the feedforward program while in free fall.

Observed differences in post-landing EMG tended to occur during time intervals that fit with theoretical expectations. It is common for post-landing EMG response time windows to be selected so that inferences can be made about the sources of muscle activation. The later responses (LLR) can be thought to be more likely a result of long-loop pathways descending from the brain since they have the time to receive and process sensory data (Cordo, 1990), while the shorter time windows (SLR, MLR) would not have enough time to complete these loops and therefore can be inferred as mostly resulting from shorter-loop spinal pathways. No differences in activation magnitude were observed during the SLR across all recorded skeletal muscles showing a threshold of time required post-touchdown before tangible changes could be produced. Observed changes in the LLR intervals were less likely the result of differences in spinal reflex arc magnitude as the reported approximately 35-50ms of time required for dynamic intrafusal fibers of the muscle spindles to be activated (Santello, 2005) would have already passed and are more likely responsible for the changes seen in the MLR window.

The findings of the present investigation provide further insight into the motor control of landing impacts. Further investigation is needed to continue developing our understanding about how limited vision leads to an observed change in muscle activation and ground reaction forces. Data like this informs us more about how potential missed landings and injuries can occur in sport or falls during daily life and can also inform clinicians more about how to optimize programs to better treat and prevent such injury. A suggestion for additional study would be to evaluate stroboscopic eyewear within the context of efficacy as a tool to train athletes to be less reliant on vision. If stroboscopic occlusion can effectively replicate movement in a visually distracting athletic environment, then our findings mean it could be desirable to train athletes to be less reliant on vision to avoid this disruption and potential increased risk of injury.

There were some limitations to this study. First, we elected to use 3 Hz stroboscopic vision as opposed to lower frequency settings that occlude vision for longer durations of time and thus are considered higher intensity. It is possible that larger effects on GRF and EMG measures could have been observed with higher intensities of stroboscopic visual occlusion. For example, when compared with full vision, Kroll et al. (2020) observed larger effect sizes on RSI scores, jump height, ground contact time, peak GRF, and RFD when DJs were performed with a 1.75 Hz strobe intensity versus 4 Hz. We elected to use a 3 Hz strobe intensity since the drop height in the present investigation was more than 30% higher than the drop height from Kroll et al. (2020). Future studies may include DJs performed with varying levels of strobe intensity to identify whether there is a threshold of visual occlusion leading to more prominent effects on neuromuscular activation and foot-ground kinetics.

A second limitation is that true drop height was not included as a possible covariate, or moderating, variable. Participants may have expressed a tendency to lower themselves more before dropping when performing DJs with stroboscopic vision as a protective mechanism, which has been observed previously for DJs performed at increasingly higher drop heights (Louder et al., 2019). Knowing that the dependent measures in the present investigation can be influenced by drop height (Santello, 2005), systematic differences in true drop height across visual conditions could lead to a misrepresentation of GRF and EMG signals, which may also lead to incorrect inferences regarding the effects of visual condition. Thus, it is suggested that future studies consider accounting for the true DJ drop height by controlling for this variable in statistical analysis.

A third limitation of the present investigation is that EMG RMS activation magnitudes were estimated from discrete time bins (e.g. pre, SLR, MLR, LLR), which may have affected the strength of statistical findings. While these time intervals are commonly used to organize EMG signals temporally to make inferences about neural origins, they are not rigid and were selected following a review of previous literature (Santello & McDonagh, 1998). Modifying the bin margins or processing EMG signals with alternative techniques (e.g. integrated EMG) may have led to different statistical findings.

Also important to note is that our study included 20 participants. Despite conducting an a priori power analysis, it is possible that this sample size did not provide a sufficient level of statistical power for detecting effects of stroboscopic vision that would have been observed with a larger sample size. Additionally, future studies may consider recruiting a sample comprised of a narrower margin of activity level or limited to a single biological sex. For instance, we included a mixed-sex sample in the present study, yet there are known differences in DJ performance across sexes (Polakovičová et al., 2018). Lastly, another suggestion for future investigation is to consider including kinetic and kinematic data at the joint level. From the perspective of replicating the present investigation, it would have been more informative to quantify the mechanics of the limbs in 3-dimensional space concomitant with the EMG latency responses. For instance, observable changes in joint-level mechanics may facilitate explanation of differences in muscle activation, which would allow greater inference into the effects of an experimental condition of stroboscopic vision on motor control.

## Conclusion

It was hypothesized that performing the DJ under condition of stroboscopic vision would result in increased peak GRF, RFD, and PFR. Results confirmed that the hypothesis was correct regarding GRF, with an observed increase that was equivalent to approximately a third of normalized body weight, on average, under stroboscopic vision. Our hypothesis was not confirmed for RFD and PFR with no significant difference seen between conditions. It was also hypothesized that there would be a decrease in preparatory muscle activation prior to landing resulting from a more cautious motor plan selected under condition of stroboscopic vision. Our findings did not agree with these hypotheses as muscle activity was found to increase in the VL during descent under testing conditions. Lastly, it was hypothesized that post-landing muscle activation would decrease with the largest effects observed during the SLR. Our results showed that the stroboscopic condition seemed to have no effect on SLR while having significant effects on the MLR and LLR windows.

The findings from this study support the position that vision is important for the motor control of depth jumps within the context of both feedforward prediction and feedback correction. When viewed collectively, the trend toward increased VL pre-activation may have contributed to an increase in peak GRF expressed during landing impact. This increase was responded to by subsequent changes in muscle activation with the TA being inhibited during the MLR window, and a higher hamstring to quad activation ratio being used during the LLR window. Using the DJ as a free-fall paradigm to replicate real life dynamic movements, the results of the present investigation further elucidate how visual disruption may lead to improper landings that could potentially contribute falls or injury in sport.

References

Baudry, S., & Duchateau, J. (2012). Age-related influence of vision and proprioception on Ia presynaptic inhibition in soleus muscle during upright stance. *The Journal of Physiology*, *590*(21), 5541–5554. https://doi.org/10.1113/jphysiol.2012.228932

Cordo, P. J. (1990). Kinesthetic control of a multijoint movement sequence. *Journal of Neurophysiology*, *63*(1), 161–172. https://doi.org/10.1152/jn.1990.63.1.161

Duncan, A., & McDonagh, M. J. (2000). Stretch reflex distinguished from pre-programmed muscle activations following landing impacts in man. *The Journal of Physiology*, *526 Pt 2*, 457–468. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00457.x

Duysens, J., Clarac, F., & Cruse, H. (2000). Load-Regulating Mechanisms in Gait and Posture: Comparative Aspects. *Physiological Reviews*, *80*(1), 83–133. https://doi.org/10.1152/physrev.2000.80.1.83

Galindo, A., Barthèlemy, J., Ishikawa, M., Chavet, P., Martin, V., Avela, J., Komi, P. V., & Nicol, C. (2009). Neuromuscular control in landing from supra-maximal dropping height. *Journal of Applied Physiology*, *106*(2), 539–547. https://doi.org/10.1152/japplphysiol.90776.2008

Grooms, D. R., Chaudhari, A., Page, S. J., Nichols-Larsen, D. S., & Onate, J. A. (2018). Visual-Motor Control of Drop Landing After Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training*, *53*(5), 486–496. https://doi.org/10.4085/1062-6050-178-16

Haeufle, D. F. B., Schmortte, B., Geyer, H., Müller, R., & Schmitt, S. (2018). The Benefit of Combining Neuronal Feedback and Feed-Forward Control for Robustness in Step Down Perturbations of Simulated Human Walking Depends on the Muscle Function. *Frontiers in Computational Neuroscience*, *12*, 80. https://doi.org/10.3389/fncom.2018.00080

Helm, M., Ritzmann, R., Gollhofer, A., & Freyler, K. (2019). Anticipation modulates neuromechanics of drop jumps in known or unknown ground stiffness. *PloS One*, *14*(1), e0211276. https://doi.org/10.1371/journal.pone.0211276

Hughes, G., & Watkins, J. (2008). Lower Limb Coordination and Stiffness During Landing from Volleyball Block Jumps. *Research in Sports Medicine*, *16*(2), 138–154. https://doi.org/10.1080/15438620802103999

Kamibayashi, K., & Muro, M. (2006b). Modulation of pre-programmed muscle activation and stretch reflex to changes of contact surface and visual input during movement to absorb impact. *Journal of Electromyography and Kinesiology*, *16*(5), 432–439. https://doi.org/10.1016/j.jelekin.2005.09.004

Kim, K.-M., Kim, J.-S., Oh, J., & Grooms, D. R. (2020). Stroboscopic Vision as a Dynamic Sensory Reweighting Alternative to the Sensory Organization Test. *Journal of Sport Rehabilitation*, 1–7. https://doi.org/10.1123/jsr.2019-0466

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Kroll, M., Preuss, J., Ness, B. M., Dolny, M., & Louder, T. (2020). Effect of stroboscopic vision on depth jump performance in female NCAA Division I volleyball athletes. *Sports Biomechanics*, 1–11. https://doi.org/10.1080/14763141.2020.1773917

Kurtzer, I. L., Pruszynski, J. A., & Scott, S. H. (2008). Long-Latency Reflexes of the Human Arm Reflect an Internal Model of Limb Dynamics. *Current Biology*, *18*(6), 449–453. https://doi.org/10.1016/j.cub.2008.02.053

Li, S., Zhuang, C., Hao, M., He, X., Marquez, J. C., Niu, C. M., & Lan, N. (2015). Coordinated alpha and gamma control of muscles and spindles in movement and posture. *Frontiers in Computational Neuroscience*, *9*, 122. https://doi.org/10.3389/fncom.2015.00122

Liebermann, D. G., & Goodman, D. (2007). Pre-landing muscle timing and post-landing effects of falling with continuous vision and in blindfold conditions. *Journal of Electromyography and Kinesiology*, *17*(2), 212–227. https://doi.org/10.1016/j.jelekin.2006.01.011

Louder, T., Thompson, B. J., Banks, N., & Bressel, E. (2019). A Mixed-Methods Approach to Evaluating the Internal Validity of the Reactive Strength Index. *Sports (Basel, Switzerland)*, *7*(7), E157. https://doi.org/10.3390/sports7070157

Mullineaux, D. R., Milner, C. E., Davis, I. S., & Hamill, J. (2006). Normalization of ground reaction forces. *Journal of Applied Biomechanics*, *22*(3), 230–233. https://doi.org/10.1123/jab.22.3.230

Nashner, L., & Berthoz, A. (1978). Visual contribution to rapid motor responses during postural control. *Brain Research*, *150*(2), 403–407. https://doi.org/10.1016/0006-8993(78)90291-3

Polakovičová, M., Vavák, M., Ollé, R., Lehnert, M., & Sigmund, M. (2018). Vertical jump development in elite adolescent volleyball players: Effects of sex and age. *Acta Gymnica*, *48*(3), 115–120. https://doi.org/10.5507/ag.2018.016

Santello, M. (2005). Review of motor control mechanisms underlying impact absorption from falls. *Gait & Posture*, *21*(1), 85–94. https://doi.org/10.1016/j.gaitpost.2004.01.005

Santello, M., & McDonagh, M. J. (1998). The control of timing and amplitude of EMG activity in landing movements in humans. *Experimental Physiology*, *83*(6), 857–874. https://doi.org/10.1113/expphysiol.1998.sp004165

Santello, M., McDonagh, M. J. N., & Challis, J. H. (2001). Visual and non-visual control of landing movements in humans. *The Journal of Physiology*, *537*(1), 313–327. https://doi.org/10.1111/j.1469-7793.2001.0313k.x

Shenton, J. T., Schwoebel, J., & Coslett, H. B. (2004). Mental motor imagery and the body schema: Evidence for proprioceptive dominance. *Neuroscience Letters*, *370*(1), 19–24. https://doi.org/10.1016/j.neulet.2004.07.053

Shih, Y., Teng, H.-L., & Powers, C. (2019). Lower Extremity Stiffness Predicts Ground Reaction Force Loading Rate in Heel-Strike Runners. *Medicine and Science in Sports and Exercise, Publish Ahead of Print*. https://doi.org/10.1249/MSS.0000000000001963

Tucker, K. J., & Türker, K. S. (2009). Muscle spindle feedback differs between the soleus and gastrocnemius in humans. *Somatosensory & Motor Research*. https://doi.org/10.1080/08990220400012489