Does providing real-time augmented feedback affect the performance of repeated lower limb loading to exhaustion?

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Research Highlights

1. We examined the effect of feedback on repeated single-leg hopping to exhaustion.
2. Tactile and visual feedbacks have a similar effect on hop height maintenance.
3. Dual feedback affects hopping cadence and height variably.

Does providing real-time augmented feedback affect the performance of repeated lower limb loading to exhaustion?

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Abstract

Introduction: This study aimed to determine whether real-time augmented feedback influenced performance of single-leg hopping to volitional exhaustion.

Methods: Twenty-seven healthy, male participants performed single-leg hopping (2.2 Hz) with (visual and tactile feedback for a target hop height) or without feedback on a force plate. Repeated measures ANOVA were used to determine differences in vertical stiffness (k), duration of flight (t_f) and loading (t_l) and vertical height displacement during flight (z_f) and loading (z_l). A Friedman 2-way ANOVA was performed to compare the percentage of trials between conditions that were maintained at 2.2 Hz ±5 %. Correlations were performed to determine if the effects were similar when providing tactile or visual feedback synchronously with the audible cue.

Results: Augmented feedback resulted in maintenance of the t_f, z_f and z_l between the start and end of the trials compared to hopping with no feedback ($p<0.01$). With or without feedback there was no change in t_l and k from start to end. Without feedback, 21 of 27 participants maintained >70% of total hops at 2.2 ± 5 % Hz and this was significantly lower ($p=0.01$) with tactile (13/27) and visual (15/27) feedback. There was a strong correlation between tactile and visual feedback for duration of hopping cycle (Spearman's $r=0.74$, $p\leq0.01$).

Conclusion**:** Feedback was detrimental to being able to maintain hopping cadence in some participants while other participants were able to achieve the cadence and target hop height. This indicates variability in the ability to use real-time augmented feedback effectively.

Keywords: audible feedback, tactile feedback, fatigue, vertical stiffness, hopping, dual-task

Introduction

The use of augmented feedback to affect motor performance is commonplace during exercise, training and rehabilitation.[1] Feedback is commonly provided during or after performance of a motor task, providing knowledge of performance or results.[2] When feedback is provided during the performance of a motor task in real-time it is thought to allow an individual to adapt their motor system instantaneously, rather than after completion of the task. This is particularly relevant to the performance of sustained and repetitive tasks such as during gait retraining[3] or tasks that may induce fatigue.

There are demonstrable changes in ground reaction force, leg spring mechanics, loading rate, kinematics and neuromuscular characteristics during running induced fatigue.[4] There is also evidence supporting the finding that fatigue induces changes in the central nervous system, such as alterations in cortical excitability.[5] Although it is not known whether these changes were deleterious or protective of the musculoskeletal system, a key strategy during training and rehabilitation has been to aim to maintain a consistent motor performance during the onset of fatigue and towards exhaustion. A recent and innovative study demonstrated that a combination of visual and auditory feedback provided in real-time, was able to influence vertical displacement and step frequency during treadmill running at 16 $km.h^{-1}$.[6] This finding suggests that augmented feedback could be an effective method for controlling or inducing changes in motor performance during a task requiring rapid and repetitive movement. Findings such as a decrease in triceps surae muscle strength[7] and lower limb kinematic changes[8] following prolonged running, provide the impetus to use real-time augmented feedback to influence motor performance which was altered. There are numerous variables such as mechanical work during running [6] that are commonly used in human movement studies. Measures which may describe performance in a motor task may also include spatiotemporal and mechanical characteristics.

The hopping task has been used to examine the effects of repeated and rapid loading of the lower limb muscles.[9] It has been reported that by simultaneously controlling hopping frequency and hop height, work output remained constant throughout double-leg hopping .[10] However, no study has evaluated the effectiveness of different types of augmented feedback to control motor performance during single-leg hopping to fatigue. Further, the efficacy of using augmented feedback to control motor performance during single-leg hopping more closely represents common gait patterns such as walking and running. Empirically determining whether motor performance is able to be controlled using augmented feedback may provide an innovative approach to investigate the effects of fatigue on the motor system during rapid loading tasks.

The dual task interference paradigm is well recognised. However, it is not known how the provision of more than one type of feedback or cue during a rapid and repeated lower limb loading task would interfere with the performance or consistency of the task. Studies have examined the dual task paradigm during performance of a number of different dynamic activities involving lower limb function such as postural control[11] and gait.[12] However, these tasks have used cognitive distraction and been most commonly performed in participants with impairment of gait and postural control, at a self-selected pace and not required rapid and repeated loading to exhaustion. Of specific interest in the current study was the use of augmented feedback which is commonplace during sporting activities and rehabilitation. Therefore, the purpose of this investigation was to determine whether real-time augmented feedback affected a change in performance and strategy of single-leg hopping to exhaustion.

Methods

Twenty seven healthy, recreationally active males (means (SD)) (22.4 years (2.7) of age, 178.6 cm (5.7) in height, 78.6 kg (11.6) in body mass) volunteered to participate in this study. Ethical approval was granted by the institutional human research and ethics committee and participants provided written and informed consent prior to testing.

All participants were male, aged between 18 and 35 years and were participating in at least 3 hours of low to moderate physical activity every week for the six month period prior to testing with the aim to control for the amount of training under load which participants had been exposed to.[13] Elite or highly trained athletes were not specifically excluded based on the inclusion criteria which were consistent with participants being exposed to a minimum level of physical activity. Participants were excluded if they reported an injury to the lower limb, back or spine in the six month period immediately prior to testing or any on-going chronic injury or pain in these regions to ensure that performance was not influenced by pain or physical impairment.

Participants wore above knee shorts and a loose fitting shirt during testing. Standing height, height to the level of the canthus and body mass were recorded. Participants conducted a warm-up that included walking overground for 5 minutes at a brisk pace (~6-8 km/h) followed by a series of lower limb and trunk static stretches.[14] All hopping trials were performed barefoot on the self-reported dominant leg.[15] Participants then performed a familiarisation period hopping on a force plate with (visual or tactile) and without feedback to hop to a target height. Participants were instructed to keep their hands on their hips and hop in synchrony with a metronome at 2.2 Hz.[16] Participants were also instructed to hop without contacting their heel with the force plate and minimising forwards, backwards and sideways translation. Familiarisation trials were performed for 10 s with a minimum 60 s rest between efforts. Each participant then completed a pre-test trial lasting 20 hops during which vertical ground reaction force (vGRF) data was recorded (Kistler 9286B data acquisition type 5691A1). This data was used to calculate the target hop height for each participant for the three trials performed to volitional exhaustion.

Real-time visual feedback was provided by placing a 1450 x 500 mm mirror in front of the force plate with a strip of tape (15 mm wide) adhered horizontally across the mirror at the top of the target hop height. For this condition, participants were instructed to hop to a height such that they could no longer see a reflection of their eyes as it was obscured by the tape. Real-time tactile feedback was provided by instructing the participant to hop to a height such that their head lightly touched a series of 5 mm wide elastic bands placed horizontally above their head. The sham feedback condition required the participant to hop with the mirror placed 2 m in front of the force plate and with a 30 mm diameter circular marker adhered over the sternum. The participant was instructed to focus their attention on the marker reflection as it was observed in the mirror in front of the participant. Viewing the marker in the mirror by the participant as they hopped did not provide any information about the target hop height.

The three hopping trials were performed in a random order and a 10 minute rest period[17] was maintained between trials to allow recovery between trials. Throughout each trial participants were instructed to maintain hop frequency with the metronome and maintain the correct hop height in the feedback conditions. No prioritisation of each requirement was instructed. Once testing was completed, each participant performed a cool-down by walking overground for 5 minutes and performing a series of lower limb static stretches.[18]

Data Processing

To calculate the target hopping height, five consecutive hops from the pre-test trial were identified and the peak vGRF for each hop cycle was labelled. The target hop height was determined as the mean of the vertical displacement of the centre of mass (COM) during flight phase (z_f) for the five hop cycles, added to the standing height of the participant (h). Equation 1 was used to determine z_f for each hop cycle (complete flight phase and subsequent contact phase).

$$z_f = \frac{1}{2} \cdot g \cdot \left(\frac{t_f}{2}\right)^2 \text{ …equation 1}$$

Where, z_f represents vertical displacement of the COM during the flight phase from peak height during flight to initial contact (IC), g was the acceleration due to gravity and t_f was the total duration of the flight phase.

The target hop height with visual and tactile feedback was calculated as z_f added to the participant's height to the lateral canthus in standing.

Vertical ground reaction force data for each trial were filtered using a Low Pass Butterworth filter with a low-pass cut-off frequency of 50 Hz (Bioware^{TM} version 5.1.0.0). The data was then exported to a Microsoft excel spreadsheet (Microsoft Excel 2010). The total hopping duration of each trial was determined. For each trial the hop cycles that were performed at 2.2 Hz ± 5% (i.e., hop cycle duration ranging from 433–478 ms) were included for the initial analyses to compare start and end periods. All hopping trials were truncated to include the first ten (start period) and last ten (end period) consecutive hop cycles performed at 2.2 Hz ± 5%. A hop cycle was defined as a complete flight phase and the subsequent contact phase. For each hop cycle the preceding cycle's toe-off (last value ≥10N), initial contact (first value ≥10N), peak vGRF (maximum value) and toe-off (last value ≥10N) were identified and labelled.[19] Temporal characteristics for each hop cycle included duration of flight phase from toe-off to IC (t_f), loading phase from IC to peak vGRF (t_l) and propulsive phase (t_p) from peak vGRF to toe-off, were determined for each hop cycle. The percentage of hops performed at 2.2 Hz ±5% was calculated by dividing the number of hop cycles with a hop cycle duration ranging from 433-478 ms by the total number of hop cycles for the trial and multiplied by 100.

Spatial characteristics (vertical displacement of the COM during flight phase (z_f) and loading phase (z_l)) for each hop cycle were then calculated. The impact velocity (v_i) was first determined using equation 2, followed by determinations of z_l using equation 3.

$$v_i = \sqrt{2 \cdot g \cdot z_f} \text{ …equation 2}$$

Where v_i represents the velocity at IC, g represents acceleration due to gravity and z_f represents vertical displacement of the COM during the second half of the flight phase.

$$z_l = \frac{1}{2}(v_i + v_f) \cdot t_l \text{ …equation 3}$$

Where, z_l represents vertical displacement of the COM during the loading phase, v_i represents the velocity at IC, v_f represents velocity at peak force and this is assumed to be 0 $m.s^{-1}$ and t_l was the duration of the loading phase.

Normalised vertical stiffness (k_N) was then calculated.

$$k_N = F_{zN}/z_l \text{…equation 4}$$

Where F_{zN} represents vGRF (peak vGRF – $vGRF_{IC}$) normalised to body mass (kg) of the participant.

Statistical Analyses

A one-way repeated measures analysis of covariance (ANCOVA) was performed to compare the total duration of hopping with the order of the hopping trial used as the covariate. A two-way (condition and period) repeated measures ANOVA was performed for all dependent variables with post hoc comparisons for each factor. Significance was accepted at $p<0.05$ with Bonferroni correction to reduce the risk of type 1 error. A Friedman two-way ANOVA was performed to compare the percentage of trials between conditions that were maintained at 2.2 ± 5% Hz and subsequent non-parametric correlations were performed to determine if the effects of tactile and visual feedback were similar with the audible cue.

Results

There was no statistically significant difference detected for total hopping duration between the three hopping conditions (mean (SD) sham feedback 74 s (32), visual feedback 68 s (27) and tactile feedback 68 s (31)) when the order of the testing condition was a covariate. At the start and end periods, t_f during tactile feedback was significantly lower than for sham feedback ($p<0.01$; $p=0.33$) and visual feedback ($p=0.01$; $p=0.02$) conditions (Table 1). The duration of flight time was significantly lower at the end than the start without feedback ($p<0.01$) and no different between periods with feedback (Table 1). Duration of loading phase was not significantly different from start to end periods for any condition and was significantly lower during sham feedback compared to the tactile condition ($p=0.04$) (Table 1). The duration of the propulsive phase was not significantly different between conditions or time periods (Table 1).

There was no significant difference in k_N with or without feedback or between start and end periods (Table 1). However, there was a trend ($p>0.04$, when significance accepted at $p <$

0.017) for an increase in k_N between start and end periods of hopping with no feedback and visual feedback which had 16% and 23% of the variance and associated error due to the change between periods, respectively. This was in contrast to only 4% of the variance and associated error between start and end periods, when hopping with tactile feedback.

Without feedback, 21 of 27 participants maintained >70% of total hops at 2.2 ± 5 % Hz (Figure 1) and this was significantly greater (p=0.01) compared to hopping with both tactile (13/27) or visual (14/27) feedback. When comparing hopping with tactile and visual feedback, the duration of the hopping cycle was strongly correlated (Spearman's $r = 0.74$, $p \leq 0.01$).

Discussion

This study demonstrated that the height of hopping was able to be maintained using augmented feedback; however, there was a decrease in the number of hops at the pre-determined hopping cadence. Vertical stiffness was preserved from the start to end periods regardless of whether there were changes in the spatiotemporal characteristics of the participants when modelled as a spring-mass. Without dual feedback 78% of participants maintained ≥70% of hop cycles at 2.2 Hz compared to ~50% when there was also provision of feedback to achieve the target hop height. These findings demonstrate that there was a trade-off between the two desired outcomes which were to maintain the target hopping height and cadence.

The findings are suggestive of a change in attentional load appropriated to following two concurrent cues. The cost of changing attentional load has been demonstrated when assessing the speed of the walk-to-run transition with the addition of mental arithmetic which induced greater transition speeds.[20] The current study extends the notion of a dual-task interference effect being demonstrable during performance of concurrent and related motor tasks compared to performing concurrent cognitive and motor tasks.[21] Importantly, approximately half of the participants were able to achieve the target hopping cadence while attending to dual tasks. This may demonstrate variability in the response between individuals to performing concurrent and related tasks. Although a deterioration in gait pattern has been demonstrated when performing dual tasks[22], it has also been demonstrated that gait training in patients with Parkinson's disease, using a visual cue or attentional strategy, led to an improvement in stride length by instructing the patient to focus their attention on the stride length.[23] The finding by Brauer and Morris (2010) in patients with Parkinson's disease is an example of how introduction of a dual task improved motor performance, however there was a direct association between the instruction and the motor task. In contrast, attentional switching has been shown to impair responses during a task which demanded cognitive effort during performance of ongoing motor task responses.[24] This is similar to the current finding of having to land on the sound of an audible cue and reach the target hop height using tactile feedback which, although related, are two separate cues requiring the participant to switch attention.

In the current study, it is plausible that there was a mixture of strategies being used to either successfully or unsuccessfully maintain hopping cadence and height. Participants who had an interference effect may not have been able to switch their attention between the feedback for cadence and hopping height which were out-of-phase. Conversely, it is also plausible that these participants were not able to focus their attention on a single cue and develop their kinaesthetic awareness to maintain both cadence and height of hopping. Focussed attention on a single cue may provide adequate sensory information to allow dual or multitasking as demonstrated in patients with Parkinson's Disease.[23] In the current study, participants were not instructed to prioritise one cue over another. Therefore, it is plausible that a participant used focussed attention on a single cue, such as tactile or visual feedback for achieving a target hop height, coordinating the goals of achieving the target hop height and cadence by regularly switching their attention to the audible cue for cadence, as a check or corrective strategy. In this manner, during a continuous and regular task such as hopping, it may have been possible to accurately maintain the cadence and target hop height, since focussed attention is not required to follow audible feedback.[25]

The findings of the current study may not be extrapolated to other populations such as older adults or children as it has been demonstrated that these populations have relatively poor motor performance compared to young adults.[26] Further, task difficulty[27-30] has been closely associated with achieving appropriate postural control while performing a concurrent cognitive or motor task. Single-leg hopping was a relatively challenging and novel task compared to other more commonly assessed tasks such as walking.[31] Therefore, the finding that there was a dual-task interference effect in the current study supports previous studies with a similar effect during functional activities such as walking and standing, however the magnitude of the effect may be different and comparison is limited due to the differences in tasks. It has been reported that greater skill is associated with better performance during novel or challenging tasks.[29, 32] The skill level of each of the participants was not evaluated prior to undertaking the procedure and could confound or limit the application of the findings. Nonetheless, the current study did determine that maintaining hopping frequency was similar when performed as a single task only, supporting the notion of a dual-task interference effect. However, whether there were differences between participants in skill level which may have underpinned the changes observed as a dual-task interference effect are not known. The skill level of being able to perform a novel and challenging task may need to be determined or classified to determine the sensitivity of a possible dual-task interference effect.

Regulation of vertical stiffness has been used to describe the leg mechanical characteristics during bouncing gaits and may be affected if the muscles are fatigued.[14, 33] Vertical stiffness determined in the current study was similar to those previously reported.[19] Although there were changes to spatiotemporal characteristics, k_N was found to be consistent in all hopping conditions from start to end periods with less variance when tactile feedback was provided to achieve a target hopping height. This finding may be important in the utilisation of real-time augmented feedback aimed at maintaining motor performance in tasks such as running and walking to exhaustion during which there have been reported changes to vertical stiffness.[34]

The total duration of hopping was not significantly different when hopping with or without augmented feedback, suggesting that there was a similar level of physical exertion in all three hopping trials. Although there was no statistical difference detected in k_N from start to end periods, there was a trend for an increase in k_N without feedback or visual feedback compared to using tactile feedback. Findings from previous investigations have been variable with some studies reporting no change to vertical stiffness during running to fatigue[4] while other studies have reported a decrease in vertical stiffness during running to exhaustion.[35] These previous studies have evaluated running during which the cadence was self-selected and there may have been variability in the vertical displacement. During hopping, motion of the COM is primarily along the vertical axis, in contrast to running, during which there is also forward displacement. This study supports the finding that vertical stiffness remains unchanged during repeated, submaximal loading of the leg when there was maintenance of spatiotemporal characteristics.

This study demonstrated that real-time augmented feedback was effective in maintaining the height of repeated single-leg hopping to volitional exhaustion. There was less variance in performance using tactile compared to visual feedback. Real-time augmented feedback needs to be used with caution in future research or training and rehabilitation of rapid loading tasks when more than one cue is provided and each cue is aimed at yielding a separate yet related motor outcome. Providing concurrent cues may lead to degradation of one or more performance measures during training and rehabilitation. The dual task interference effect is not consistent between participants and may reflect an inherent difference in how attentional strategies are used and impact motor performance.

Conflict of Interest

The authors declare that there is no financial or other conflict of interest for this study.

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Tables

Table 1 Spatiotemporal, kinetic and vertical stiffness (mean (SD)) at the start and end periods of the sham, visual and tactile feedback hopping conditions.

	Sham		Visual		Tactile	
	Start	Finish	Start	Finish	Start	Finish
t_{cycle} (ms)	450 (11)	447 (9)	451 (13)	444 (9)	445 (14)	447 (8)
t_f (ms)	*126(24)	110 (15)	115 (26)	112 (19)	97 (24)	99 (17)
t_l (ms)	156 (14)	159 (14)	161 (18)	155 (17)	166 (14)	168 (18)
t_c (ms)	*277 (120)	337 (17)	336 (29)	333 (21)	347 (29)	348 (21)
z_f (mm)	*20 (8)	15 (4)	17^d (7)	16^d (5)	13 (6)	12 (4)
z_l (mm)	*47 (7)	43 (5)	*45 (8)	42 (6)	39 (7)	40 (5)
F_N ($N.kg^{-1}$)	24.71 (2.45)	23.61 (1.68)	23.81 (2.91)	24.20 (2.77)	21.90 (2.66)	22.27 (1.70)
k_N ($N.kg^{-1}.m^{-1}$)	0.54 (0.06)	0.57 (0.07)	0.55 (0.09)	0.60 (0.09)	0.59 (0.13)	0.58 (0.08)

*$p<0.05$ - significantly different between start and end periods; t - duration; f - flight phase; l - loading phase; c - contact phase; z - vertical displacement of the centre of mass; F_N - Normalised vertical ground reaction force; k_N - Normalised vertical leg stiffness.

Figures

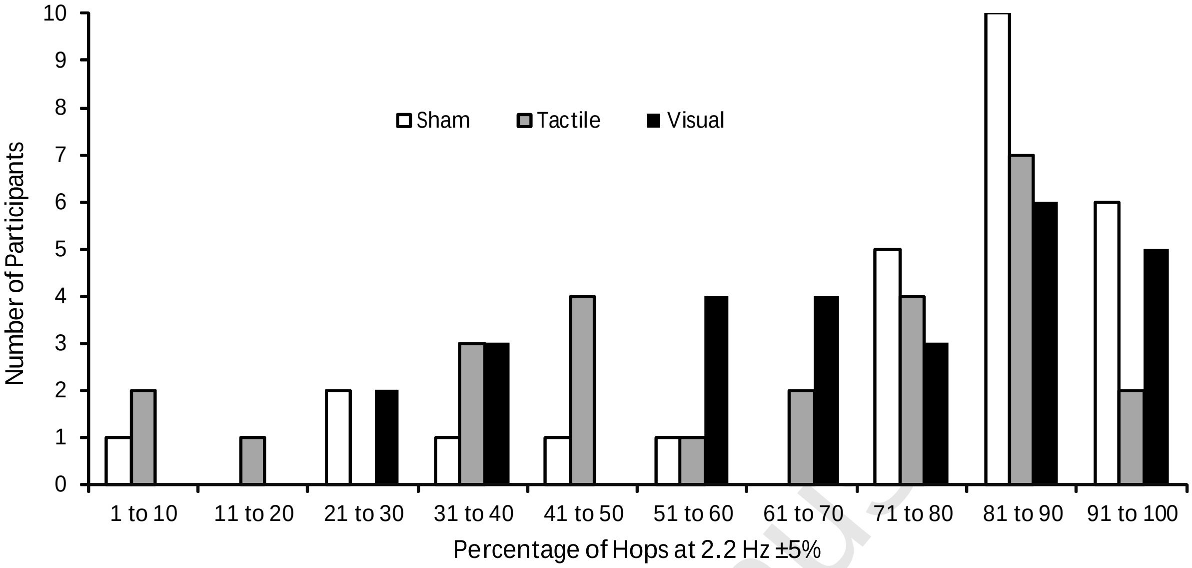

Figure 1

Captions for Figures

Figure 1 The number of participants which were able to maintain the hopping cadence at 2.2 Hz ±5% was greater when no tactile or visual feedback was provided relating to hopping to a target height.