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Contribution of afferent feedback and descending drive to human hopping

Abraham T. Zuur[1,2,3], Jesper Lundbye-Jensen[1,2], Christian Leukel[4,5], Wolfgang Taube[4], Michael J. Grey[1,2], Albert Gollhofer[4], Jens Bo Nielsen[1,2] and Markus Gruber[4,6]

[1]*Department of Exercise and Sport Sciences, Panum Institute, University of Copenhagen, Blegdamsvej 3, 2200 Copenhagen N, Denmark*
[2]*Department of Neuroscience and Pharmacology, Panum Institute, University of Copenhagen, Blegdamsvej 3, 2200 Copenhagen N, Denmark*
[3]*Center for Sensory-Motor Interaction, Aalborg University, Fredrik Bajers Vej 7-D3, DK-9220 Aalborg, Denmark*
[4]*Department of Sport Science, University of Freiburg, Schwarzwaldstr. 175, 79117, Freiburg, Germany*
[5]*Spinal Cord Injury Centre, University Hospital Balgrist, Zürich, Switzerland*
[6]*Department of Training and Movement Science, University of Potsdam, Am Neuen Palais 10, 14469 Potsdam, Germany*

During hopping an early burst can be observed in the EMG from the soleus muscle starting about 45 ms after touch-down. It may be speculated that this early EMG burst is a stretch reflex response superimposed on activity from a supra-spinal origin. We hypothesised that if a stretch reflex indeed contributes to the early EMG burst, then advancing or delaying the touch-down without the subject's knowledge should similarly advance or delay the burst. This was indeed the case when touch-down was advanced or delayed by shifting the height of a programmable platform up or down between two hops and this resulted in a correspondent shift of the early EMG burst. Our second hypothesis was that the motor cortex contributes to the first EMG burst during hopping. If so, inhibition of the motor cortex would reduce the magnitude of the burst. By applying a low-intensity magnetic stimulus it was possible to inhibit the motor cortex and this resulted in a suppression of the early EMG burst. These results suggest that sensory feedback and descending drive from the motor cortex are integrated to drive the motor neuron pool during the early EMG burst in hopping. Thus, simple reflexes work in concert with higher order structures to produce this repetitive movement.

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Corresponding author J. Lundbye-Jensen: Departments of Exercise & Sport Sciences and Neuroscience & Pharmacology, University of Copenhagen, Blegdamsvej 3, 2200 Copenhagen N, Denmark. Email: jljensen@ifi.ku.dk

Abbreviations FSR, functional stretch reflex; MEP, motor evoked potential; SLR, short latency stretch reflex; TMS, transcranial magnetic stimulation.

Introduction

In the 19th century, the neurologist Hughlings Jackson proposed that movements can be categorised somewhere on the continuum between the most automatic or evolutionarily primitive to the least automatic or most evolutionarily advanced (Hughlings Jackson, 1884). Hopping can also be placed on this continuum. On one hand it is naturally a voluntary movement, on the other hand it has been suggested to arise from simple and automated processes within the central nervous system. Muscle activity in rhythmic movements, like hopping, may indeed be generated by evolutionarily simple spinal reflexes as well as by evolutionarily more advanced supra-spinal centres and possibly the combination of both. If so, this means that hopping is not either reflexive or voluntary, spinal or cortical but that mechanisms at different levels act together to control the movement.

Melvill-Jones & Watt (1971) were perhaps the first to study the contributions of the stretch reflex in human hopping. They observed a large response around 120 ms after the sudden stretch of the triceps surae after touch-down. They concluded that this was the first useful muscular reflex response in hopping and therefore labelled this the functional stretch reflex (FSR). Based on its latency, the authors suggested that it might be mediated through supra-spinal pathways. Similar to a spinal reflex this supra-spinal reflex is strongly tied to a sensory stimulus, but the sensory stimulus can be integrated with other sensory information and instruction (Evarts & Tanji, 1974).

Apart from the FSR, Melvill-Jones & Watt (1971) reported occasional early bursts of EMG activity at a latency consistent with a simple monosynaptic reflex arc. Subsequent studies reported a consistent EMG burst starting about 45 ms after touch-down (Dyhre-Poulsen *et al.* 1991; Voigt *et al.* 1998; Funase *et al.* 2001). In these studies, the burst was suggested to be a stretch reflex response superimposed on activity of supra-spinal origin. This idea was based on the onset-latency of the burst, now commonly labelled short latency stretch reflex (SLR), and the high excitability of the H-reflex at the time of touch-down (Dyhre-Poulsen *et al.* 1991; Voigt *et al.* 1998; Funase *et al.* 2001). These observations point towards a spinal reflex contribution to the early EMG activity in hopping and this is generally accepted in the motor control literature.

In tasks involving landing in primate and human subjects, both stretch reflexes and pre-programmed activity contribute to the motor control. In this context, pre-programmed activity is defined as muscle activity that does not depend on the actual time of touch-down but on the expected time of touch-down. Such a pre-programmed pattern has been seen in monkeys that jumped onto a false platform (Laursen *et al.* 1978; Dyhre-Poulsen & Laursen, 1984). While the true landing was delayed in this paradigm, the EMG pattern remained time-locked to the time of the expected landing. In contrast, subjects stepping down on a platform showed a consistent peak of soleus EMG activity around 60 ms after touch-down while this peak disappeared when the height of step-down was unexpectedly increased, suggesting that the peak is of reflex origin (Greenwood & Hopkins, 1976). Similarly, a reflex superimposed on a pre-programmed triceps brachii EMG activity pattern has been shown in blindfolded healthy human volunteers who fell forward on a platform in which the depth of the platform was randomly varied (Dietz *et al.* 1981). Support for a spinally generated reflex contribution has also been provided by Duncan & McDonagh (2000), who investigated landings with a false floor. In this case, the subjects fell further than expected and did not produce the normal EMG burst that occured ~55 ms after landing. Primate and human studies demonstrate that pre-programmed activity is involved in landing while the human studies suggest an additional stretch reflex contribution. It is not clear if this is also true for hopping, because the motor control of hopping and landing are not necessarily the same, as exemplified in the different H-reflex modulation and kinematics (Dyhre-Poulsen *et al.* 1991).

Little is known about the origin of the pre-programmed activity in hopping. Cortical contributions to a repetitive task have been shown in walking (Petersen *et al.* 2001) and suggested in drop jumps (Taube *et al.* 2008). Taube *et al.* (2008) observed a very low corticospinal excitability shortly after touch-down, which increased towards take-off. Conversely, the H-reflex excitability was high at the beginning of ground contact but decreased towards take-off. Based on these observations we can speculate that the motor cortex also contributes to the early EMG burst in hopping.

Thus, there are indications that both reflexes and the cortex may be involved in the control of human hopping. We may speculate that structures on the extremes of Hughling Jackson's continuum work in concert to generate the EMG in the early EMG burst during hopping. In the present study we first investigate the stretch reflex contribution to hopping. Here, we hypothesised that if a stretch reflex contributes to the early EMG burst, then advancing or delaying the touch-down should similarly advance or delay the burst. We advanced or delayed the touch-down by shifting the height of a programmable platform up or down between two hops, without providing the subject with clues about the position of the platform. In the second part of the study, we clarified if the motor cortex plays a role in the generation of the early EMG burst. We hypothesised that if the motor cortex contributes to the first EMG burst during hopping, inhibition of the motor cortex would reduce the magnitude of the burst. To test this hypothesis, corticospinal neurons were inhibited using subthreshold transcranial magnetic stimuli (Davey *et al.* 1994) timed to coincide with the EMG burst immediately after touch-down.

Methods

The experiments were performed in 19 healthy volunteers (12 male, 7 female; aged 21–37 years). The experimental procedure was approved by the local ethics committee and all subjects gave informed written consent prior to participation. The experiments were conducted in accordance with the latest revision of the *Declaration of Helsinki.* Protocol 1 was conducted under ref. no. H-A-2008-029 and protocol 2 under ref. no. VN2004/4.

EMG

EMG activity was recorded from the soleus (SOL), tibialis anterior (TA) and gastrocnemius medialis (GM) of the dominant leg using Ag–AgCl electrodes (1 cm^2, inter-electrode distance 1 cm). EMG signals were transmitted wirelessly to an amplifier system (Aurion ZeroWire, Noraxon, Scottsdale, AZ, USA), amplified (×1000), filtered (25–1000 Hz), digitized, sampled at 4 kHz and stored together with the kinematic data on a PC for off-line analysis.

Kinematics and ground reaction force

All recordings and stimulations were triggered by an Optojump photoelectric light barrier system (Microgate,

Bolzano, Italy) positioned 3 cm above the force platform. During the experiments, joint angles were monitored by electro-goniometers (Biometrics Ltd, Cwmfelinfach, UK) placed at the ankle and knee joints of the dominant leg. The goniometer axis of rotation was carefully aligned with the rotational axes of the ankle and knee joints. The vertical ground reaction force (Fz) was obtained using a force platform (Advanced Mechanical Technology, Inc. (AMTI), Watertown, MA, USA) and amplified with a MINI AMP amplifier (AMTI).

Hopping instructions

After 1 min of warming up with low-intensity hopping, subjects were asked to hop with gradually increasing height from low to maximum in order to select a hopping height at which EMG activity in the plantar flexor muscles showed a clear burst. Subjects were instructed to hop with this effort and with active plantar flexion and limited flexion in the knee joints throughout the whole experiment. Subjects were instructed to look straight ahead to a fixed target on the wall. One session consisted of approximately 60–80 hops. A rest of approx. 3 min between the sessions was mandatory to avoid fatigue.

Protocol 1: moving platform

Nine subjects participated in this protocol. Subjects were instructed to look straight ahead and hop on a hydraulically actuated platform (van Doornik & Sinkjaer, 2007). For safety reasons and to control that the subject was looking straight ahead during hopping, an experimenter was standing next to the subject for the full duration of the experiment. During the period the subject was in the air the platform either stayed in the levelled position (control trials) or moved 2.5 cm up or down in a randomised fashion. In the control trials the platform made a lateral movement but returned to the level position before the subject touched down, so that in all three conditions the same sound was made and no audible cues were given about the position of the platform.

Protocol 2: transcranial magnetic stimulation

In the current study we investigated cortical involvement by applying TMS with a subthreshold intensity to suppress the output from the motor cortex. Davey *et al.* (1994) were the first to demonstrate that a single transcranial magnetic stimulus below the threshold to elicit a motor evoked potential (MEP) can produce a suppression in the EMG of a voluntarily contracted muscle without prior facilitation. Several control experiments suggested that this TMS-evoked EMG suppression is due to the activation of intracortical inhibitory interneurons which suppress the output from the motor cortex (Davey *et al.* 1994; Petersen *et al.* 2001).

Thirteen subjects participated in this protocol. Magnetic stimuli were delivered to the primary motor cortex by a Magstim Rapid 2 stimulator (Magstim Co. Ltd, Whitland, UK) via a custom-made 90 mm double coil (batwing design, Magstim Co.) placed over the spot where a magnetic stimulus gave a maximal response in the SOL with the handle of the coil pointing backward, so that the current in the brain flowed in a posterior–anterior direction. The coil was kept in position with a custom-made climbing helmet (Petzl, Garmisch-Partenkirchen, Germany). The helmet was tightly attached to the head with a fixation system attached to the helmet and additionally secured by straps over the chin and to the back of the head. To alleviate the weight added onto the subject, the coil, the cable of the coil and the helmet were suspended from the ceiling by elastic bands. Frameless stereotaxy (Brainsight, Rogue Research Inc., Montreal, Canada) allowed precise on-line monitoring of coil position and orientation with respect to the head. With this system the coil position was maintained within 2 mm of the target. In addition, a 2D high speed optoelectronic Vicon camera (Vicon Motion Systems, Oxford, UK) operating at 250 frames s^{-1} was used to confirm with high time resolution that the coil did not move in the coronal plane during the experiment. TMS stimulations were timed with constant delay relative to the trigger from the light barrier system so that the TMS stimulus was delivered approximately 45–50 ms prior to the peak of the early EMG burst. Since a suppression in the SOL EMG follows approximately 40 ms after a subthreshold pulse (Petersen *et al.* 2001), the onset of the suppression was expected approximately 5–10 ms before the peak. The initial magnetic stimuli were always high enough to show a facilitation in the averaged trials. As soon as a facilitation was observed in the rectified or unrectified SOL, GM or TA EMG, the stimulus was decreased again and a new recording was started. In this way the stimulus intensity was decreased to an intensity at which a suppression was seen without any evidence of facilitation. In the recordings of the final intensity, at least 80 stimulated and 80 control trials were recorded in a randomised fashion.

Analysis

The peak of the early EMG burst was derived from the ensemble averaged EMG and was defined as the highest point in a window 40 ms after the first major deflection of the EMG. The onset of EMG was defined as $>50\ \mu V$ in the ensemble average EMG.

The touch-down on the platform in the individual hops was defined as the point where the vertical force exceeded 3 times the standard deviation of the force 100 ms prior to

the subject crossing the light barrier, when the subject was in the air. To obtain the time point at which the sudden dorsiflexion movement of the ankle occurred following touch-down, the ankle angle (α) of each individual hop was filtered with a second order 40 Hz low pass filter and differentiated. This was done twice with the signal once reversed in time, so that time shift due to filtering was minimised. The resulting second derivative of α was labelled $\ddot{\alpha}$. Plantar flexion was defined as a positive change and dorsiflexion as a negative change, and thus minimal $\ddot{\alpha}$ reflects the time point of the maximal dorsiflexion acceleration. We chose to use min $\ddot{\alpha}$ in the analysis because the fast monosynaptic reflex arc is thought to mediate afferent information from the intrafusal muscle fibres concerned with the velocity of the length changes of the muscle (Berardelli *et al.* 1982; Gottlieb *et al.* 1983). The time points of minimal ankle angle accelerations in the up or down condition were averaged and compared with the average of the levelled condition. The time difference between the peak of the burst in the ensemble averaged SOL EMG in the levelled position and SOL EMG peak in the condition with the platform up or down was calculated. The time shift of the peak was plotted against the time shift of min $\ddot{\alpha}$ and a regression line which was going through the origin was fitted through the data points. If a time shift in the peak is equal to the time shift in min $\ddot{\alpha}$ this regression line should be equal to 1.

The onset of the TMS-evoked EMG suppression and the start of the analysis window were defined as the point where the ensemble-averaged EMG for the stimulated condition was less than the control EMG for at least 4 ms in a window from 30 to 60 ms after the transcranial stimulus. Short lasting suppressions (< 4 ms) were difficult to visually separate from drops in the EMG due to natural variation of the signal and were therefore excluded from further analysis. The end of the suppression was defined as the time when the stimulated EMG was above the control EMG for more than 1 ms. The mean of the control condition was defined as the mean EMG of the ensemble averages in the window of analysis. The maximal suppression was defined as the point where the difference between the ensemble averages of the stimulated and the control trials was largest. The mean and maximum of the suppression were expressed as percentage change $(\text{control} - \text{stimulated})/\text{mean}_{\text{control}} \times 100$.

Statistics

To test for difference between the variables in the moving platform protocol (up, levelled, down) a one-way repeated measure analysis of variance (rmANOVA) was used. To test for differences in the TMS protocol (control *vs.* stimulated) a two-sided Student's t test for paired data was used. All results in the text are given as means ± standard deviation, while the results in Fig. 3 are given as means ± standard error of the mean for display reasons.

Results

The average hopping height of the subjects was 24 ± 3 cm (range 19 to 28 cm). At these hopping heights a prominent early EMG burst within 100 ms after passing the light barrier could always be detected. The passing of the light barrier was followed by touch-down 30 ± 7 ms later, when the platform was in the levelled position.

Protocol 1: moving platform

Figure 1 shows the raw and ensemble averaged EMG of a single subject. While SOL shows a distinct early burst, such a burst was less distinct in the ensemble averaged GM, which is in accordance with observations from Voigt *et al.* (1998). The focus in the analysis was therefore on SOL. It can be observed in the ensemble averages that when the platform was in the up-position both the touch-down and the minimum acceleration of the ankle angle advanced in time, while they were delayed in the down-position. The peak of the early EMG burst shifts in the same direction. Figure 1 shows that the EMG onset relative to the crossing of the light barrier was not different between conditions, which was also observed in the group analysis (1 ± 18 ms; $F_{2,8} = 0.490$; $P = 0.62$). The group average of the onset of the SOL EMG in the levelled position is 27 ± 25 ms prior to touch-down and thus well before a reflex component induced by touch-down can contribute to the EMG.

The relationship between shift in min $\ddot{\alpha}$ and the peak in the EMG for all subjects is displayed in Fig. 2. A shift in min $\ddot{\alpha}$ resulted in a corresponding shift in the peak of the early EMG burst. This relationship is confirmed by a regression line through the origin which was fitted through the data points. A regression coefficient of $r^2 = 0.94$ was obtained and the slope was found to be 1.05 (95% confidence intervals: 0.91–1.18). Additionally, the regression line between the peak and the touch-down was calculated. In this analysis a slope of 0.94 was found (confidence intervals: 0.75–1.12) and a regression coefficient of $r^2 = 0.87$. These confidence intervals include the hypothesised slope of 1. That the time shift in min $\ddot{\alpha}$ is accompanied by a time shift in the peak is in line with the idea that a stretch reflex contributes to the early EMG burst in hopping. The timings of the platform protocol are displayed on the white background of Fig. 3. Figure 3*A* shows that touch-down was advanced in the up condition and delayed in the down condition. These changes were significantly different from the levelled position ($F_{2,8} = 71.5$; $P < 0.001$). Figure 3*B* shows that also min $\ddot{\alpha}$ ($F_{2,8} = 93.3$; $P < 0.001$) and peak of the EMG burst ($F_{2,8} = 264.8$; $P < 0.001$) are significantly

shifted relative to the crossing of the light barrier in the different positions of the platform. The bars in Fig. 3*B* show the period between min $\ddot{\alpha}$ and the peak in the EMG, which was on average 41 ± 6 ms. This period did not change between the different conditions ($F_{2,8} = 0.34$; $P = 0.72$). The latency between touch-down and the peak of the EMG burst was on average 53 ± 7 ms without a significant difference between the different conditions ($F_{2,8} = 0.85$ $P = 0.45$). This absence of a change in latency is consistent with our hypothesis that a time shift in min $\ddot{\alpha}$ is accompanied by an equal time shift in the peak of the EMG burst.

Protocol 2: TMS

Figure 4 shows an example of a TMS-evoked EMG suppression in SOL during hopping in a single subject. A suppression with a duration of 7 ms is evident in SOL and suppressions of 6 ms and 7 ms can be seen in GM and TA, respectively. The onset of the suppression in TA

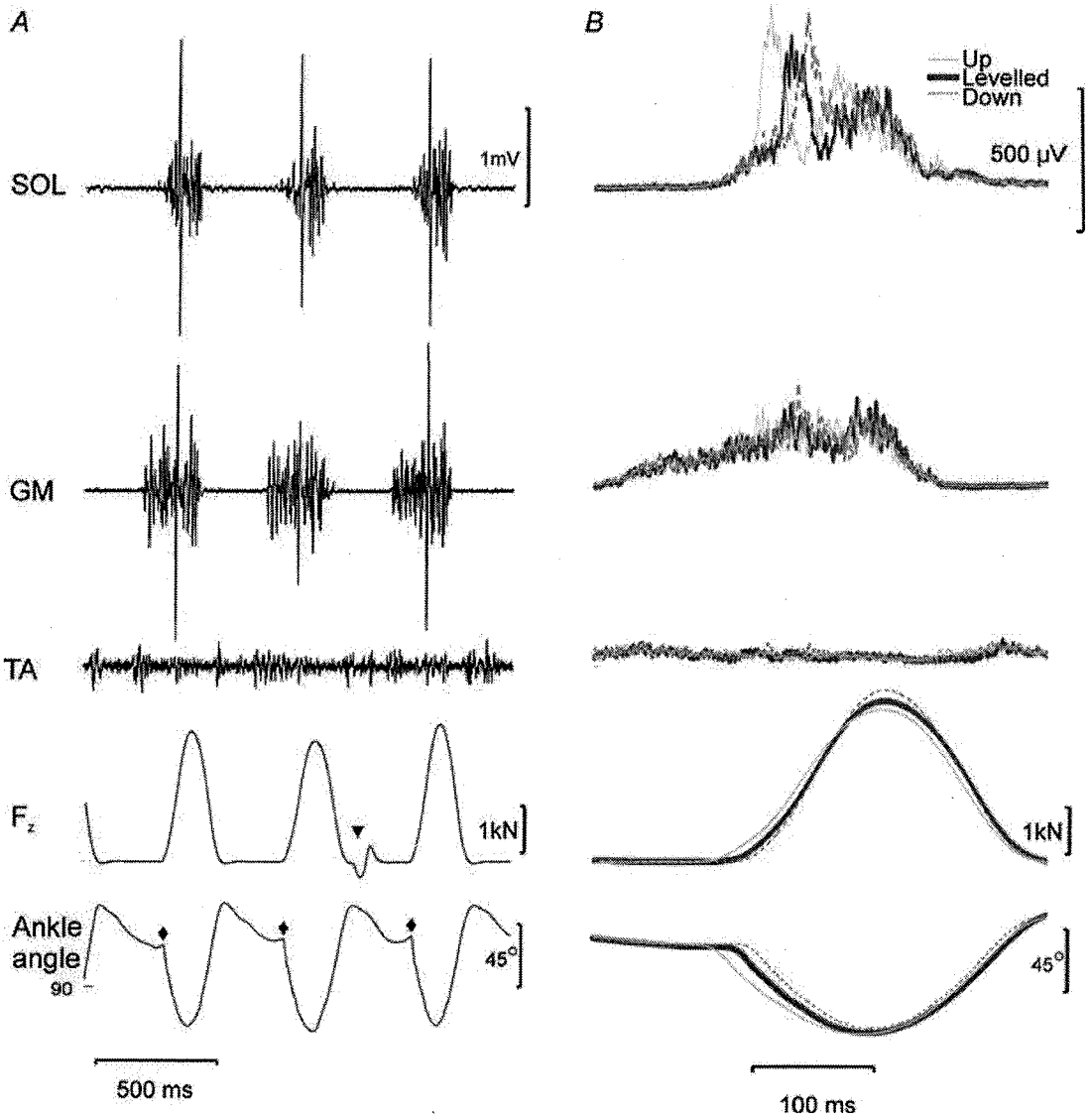

Figure 1. Raw and ensemble averaged EMG and kinematics during hopping in a single subject
A, raw EMG and kinematics from three hops. ▼ indicates an artefact in the force signal due to acceleration and deceleration of the platform. ♦ indicates the point where the ankle angle shows a maximal dorsiflexion acceleration (min $\ddot{\alpha}$). *B*, ensemble average of 25 sweeps for the conditions 'Up', 'Level' and 'Down'. All averaged trials are aligned to the crossing of the light barrier. Note that the platform in the 'Up' position causes a shift in the signals for ankle angle, ground reaction force and the EMG burst in SOL ahead in time whereas the 'Down' position delays these signals in time.

and GM is within 1 ms from the onset of the suppression in SOL. The suppression is thought to be mediated by intracortical inhibitory interneurons (Davey *et al.* 1994; Petersen *et al.* 2001) and a suppression of the EMG would be in line with a contribution from the motor cortex to the early EMG burst in hopping. After the suppression in SOL a rebound peak can be observed, which has a similar shape as the peak in the control EMG, but with a delay of 7 ms. Based on this delay it may be speculated that the TMS delays the motor programme producing the peak. In many of the other subjects, however, such a similarity between the peak in the control EMG and the peak in the stimulated EMG was not seen. In 3 out of the 13 subjects, no suppression in SOL could be evoked and those subjects were not included in the rest of the analysis. The intensity at which a suppression without facilitation was observed was 41 ± 8% of the maximal stimulator output.

The shaded areas in Fig. 3 display the onset and duration of the suppression and its time relation to min $\ddot{\alpha}$, touch-down and peak of the EMG burst. The average duration of the suppression was 8 ± 3 ms. No difference in timing of touch-down ($P = 0.11$) and min $\ddot{\alpha}$ ($P = 0.14$) was seen between the trials with and without TMS. The mean suppression was on average 15 ± 5% and the maximal suppression 28 ± 6% of the control EMG.

Although the primary goal was to evoke a suppression in the SOL EMG, the EMG of the GM was also suppressed by TMS at the same stimulus intensity as used to suppress SOL EMG in 7 out of 11 subjects. In two subjects the TA and GM were not recorded. The average suppression in GM in the seven subjects who showed a suppression was 15 ± 5% and the maximal suppression was 30 ± 7%. Four out of eleven subjects showed a distinct suppression of longer than 4 ms in the TA.

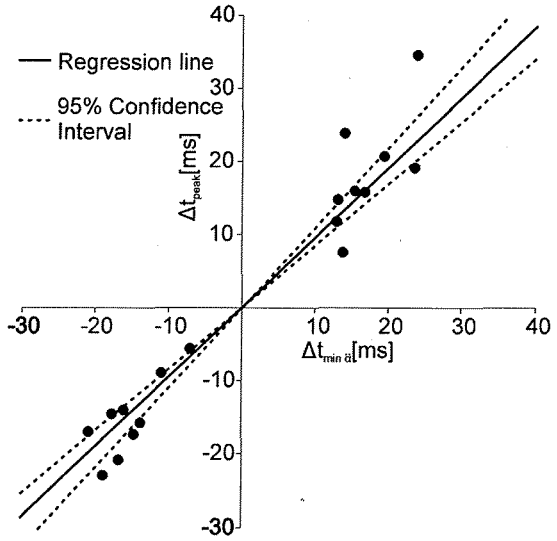

Figure 2. Correlation between the shift in min $\ddot{\alpha}$ ($\Delta t_{min\ \ddot{\alpha}}$) and the peak of the EMG burst (Δt_{peak})
Each subject is represented by two data points, one for platform up and one for platform down. Positive numbers indicate the situation in which the event (min $\ddot{\alpha}$ or EMG peak) is delayed compared to the level position (platform down); negative numbers are situations in which those events are shifted ahead (platform up).

Discussion

In the present study we investigated the reflex and cortical contributions to the control of hopping. The time shift in touch-down caused by an unexpected shift in platform height, resulted in an equal time shift in the peak of the early EMG burst, thus confirming our hypothesis and demonstrating that stretch reflexes contribute to the early burst. Inhibition of the motor cortex with subthreshold TMS reduced the magnitude of the early EMG burst,

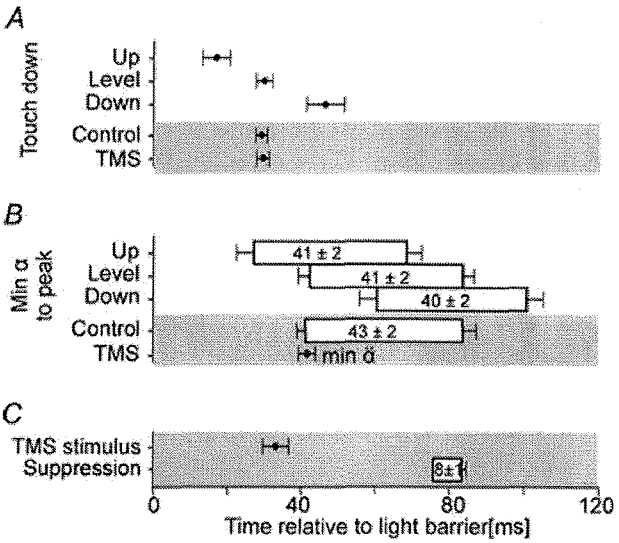

Figure 3. Averaged time points during hopping with time 0 indicating the crossing of the light barrier
The white background indicates the moving platform protocol. 'Up', 'Level' and 'Down' refer to the position of the platform. The grey background indicates the TMS protocol, 'Control' refers to unstimulated trials and 'TMS' refers to trials with a subthreshold TMS stimulus. Error bars at the start and end of the bar indicate the S.E.M. of the time of that event relative to the crossing of the light barrier, while the numbers written in the bar indicate the time between the events ± S.E.M. *A*, the timings of touch-down detected by the vertical force on the platform ± S.E.M. In *B* the beginning of the bar shows the time of min $\ddot{\alpha}$ and the end indicates peak of the early EMG burst and thus the length of the bar indicates the duration between those events. It can be seen that the time between min $\ddot{\alpha}$ and the peak of the early EMG burst remains the same in the three conditions. Only the time of min $\ddot{\alpha}$ is displayed in the stimulated condition of the TMS protocol since the position of the peak is concealed by the after-effects of the suppression. In *C* 'TMS stimulus' indicates the time point where the TMS stimulus is delivered. 'Suppression' represents the average timing and duration of the suppression. By comparing it with the control condition in Fig. 3*B*), it can be seen that the suppression is timed just prior to the peak of the early EMG burst.

suggesting that the motor cortex also contributes to the first EMG burst.

A potential methodological limitation with our first protocol (moving platform) is that subjects may have anticipated the position of the platform and changed their motor programme prior to touch-down. However, anticipation is unlikely for at least three reasons. First, the platform height for each hop was randomised. Second, the sound made by the platform was the same in all conditions, thus eliminating the possibility of an audible cue. Visual cues about the position of the platform were also removed by requiring the subject to look at a target fixed to the wall. None of the subjects reported that they were able to anticipate the movement of the platform or to pick up cues about the position of the platform. However, the awareness that the platform would move in between the hops possibly altered the neural control compared to hopping on a level floor.

Our results are in line with observations from landing where the EMG burst that appears shortly after landing disappeared when the subjects fell through the false floor, thus confirming that the burst results from a stretch reflex (Duncan & McDonagh, 2000). In the present study, we observed a latency of 53 ± 7 ms between the SOL EMG peak and touch-down, which is comparable to the 56 ± 2 ms latency observed by Duncan & McDonagh (2000). These authors reported that this EMG peak was approximately 4 ms later than the EMG peak of stretch reflexes elicited with passive rotations of the ankle joint while subjects performed a tonic contraction. The latencies in the present study are also comparable to the SLR latencies of the triceps surae observed after a dorsiflexion

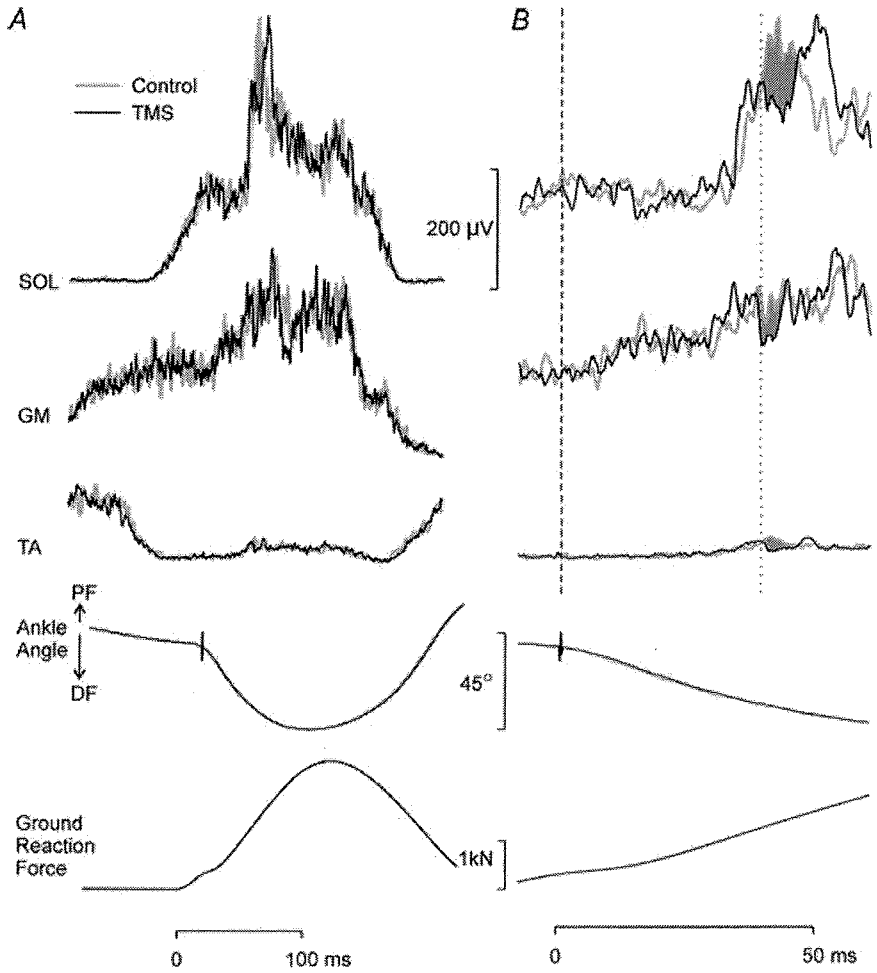

Figure 4. TMS-evoked EMG suppression during the early EMG burst
A, ensemble averaged EMG and kinematic data (80 sweeps) of the stimulated and unstimulated condition from a single subject showing a TMS-evoked EMG suppression in SOL, GM and TA (shaded). Time 0 is aligned with ground contact. *B*, the same data zoomed in the *x*-direction. The dashed line indicates the time of the TMS stimulus and the dotted line the onset of suppression.

perturbation during sitting (Agarwal & Gottlieb, 1980; Berardelli *et al.* 1982). Therefore, we can postulate that there is a large overlap between the pathways mediating the early EMG burst in hopping and the SLR elicited during sitting. Petersen *et al.* (1998) calculated that the minimum time for a transcortical stretch reflex in the TA is most likely to be over 75 ms in most subjects. Since the distance between cortex and SOL is comparable to the distance between cortex and TA, a similar latency is to be expected for a transcortical stretch reflex in SOL. The latency of the observed burst is therefore too short to be mediated by a transcortical pathway.

A potential methodological concern with our second protocol (TMS) is that the magnetic stimuli may suppress the EMG via other mechanism than through inhibition of the motor cortex. The most parsimonious explanation for EMG suppression is the excitation of intracortical interneurons, thus reducing cortical output, although it is possible that the effect is mediated through inhibitory interneurons at a subcortical or spinal level. Nevertheless, control experiments in other studies have provided evidence for a cortical origin of the TMS-evoked suppression. It was possible to suppress EMG in the leg with TMS, but not with transcranial electric stimulation (TES), which is thought to stimulate the corticospinal axons directly (Petersen *et al.* 2001). Moreover, electrical stimulation of the cervical spinal cord does not evoke similar suppressions in the arm (Davey *et al.* 1994). Both studies suggest that the inhibitory effect is supra-spinal, most likely of cortical origin. Similar to Davey *et al.* (1994) we observed a suppression of the antagonist muscle in some subjects, while none of our subjects showed a facilitation in this muscle. This observation contradicts the suggestion that the TMS-evoked EMG suppression would be mediated by spinal reciprocal interneurons. Therefore, the EMG suppression at the time of the burst strongly supports a cortical drive in hopping.

SOL EMG may already be observed prior to touch-down and the onset of this EMG activity is independent of the platform position. This activity may therefore be labelled as pre-programmed and may well have a supra-spinal or cortical origin. While we show in the current study that the motor cortex contributes to muscle activity at the time of the early EMG burst, it may be that such a contribution from the motor cortex is present throughout the hopping cycle.

Thus, part of the drive to the motor neuron during the early EMG burst in hopping originates from the motor cortex, but for what in turn drives the motor cortex there is a wide range of possibilities. While these sources might present a true pre-programmed pattern, it could also be of vestibular or visual origin (McKinley & Smith, 1983) or it may be of proprioceptive origin. Such sources would be closer to reflex and the term (pre-)programmed might be misleading. This underlines that it is not always clear-cut to separate reflex and programmed (Prochazka *et al.* 2000). Nevertheless, we can conclude from the present study that both spinal reflexes and the motor cortex contribute to the early EMG burst in hopping. These contributions can be placed at each extreme of the continuum postulated by Hughlings Jackson more than 125 years ago (Hughlings Jackson, 1884).

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Author contributions

A.T.Z., J.L.J., C.L., W.T., M.J.G., J.B.N. and M.G. contributed to the conception and design of the experiment. A.T.Z., J.L.J., C.L., W.T., M.J.G., J.B.N. and M.G. contributed to the collection, analysis and interpretation of data. A.T.Z. and J.L.J. drafted the article. All authors critically revised the manuscript for important intellectual content and all authors approved the final version for publication. Protocol 1 was carried out at the Center for Sensory-Motor Interaction at Aalborg University. Protocol 2 was carried out at Panum Institute, University of Copenhagen.

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