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MUSCULAR CONTROL OF LANDING FROM UNEXPECTED FALLS IN MAN

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SUMMARY

1. It was previously shown that the controlled landing from single steps to the ground is typically brought about by accurately timed motor activity, commencing before the actual landing, and completed before time would permit the participation of a useful stretch reflex response.

2. To investigate further the validity of this conclusion, subjects were dropped from an electromagnetic suspension at unexpected moments. Their gastrocnemius electromyographic (e.m.g.) responses and the forces applied to their feet were recorded throughout.

3. No useful contribution of a stretch reflex response was detected. Indeed, it was shown that a functionally effective reflex resulting from the mechanical event of landing would occur far too late to contribute to the muscular deceleration of the fall.

4. It was also found that a consistent muscular response occurred, commencing 74·2 msec (S.E. of mean = 1·4 msec) after starting the fall, independent of height.

5. It is suggested that this response in the leg musculature is a reflex originating in the otolith apparatus. In addition, a possible mechanism for the control of repetitive hopping, and perhaps running, movements, involving the above reflex, is suggested.

INTRODUCTION

In 1924, Liddell & Sherrington described a stretch, or 'myotatic', reflex in the decerebrate cat, and later Renshaw (1940) demonstrated a segmental monosynaptic pathway through which such a reflex could operate. However, in 1956 Hammond, Merton & Sutton demonstrated that on suddenly and unexpectedly stretching the human biceps muscle, the first functionally useful tension was not due to a monsynaptic response, but to a later, more complex, reflex contraction.

In a previous paper, Melvill Jones & Watt (1971) demonstrated a similar response in the leg which was described as the Functional Stretch Reflex (FSR). However, the FSR was found to occur too late to play a useful role in the arrest of a landing from a single step or jump to the ground. Indeed, it seemed that during such a manoeuvre there may have been an active inhibition at the time when the FSR would have been expected to occur as a result of the muscle stretch on landing. These results led to the conclusion that the muscular deceleration during such a landing was essentially brought about by an accurately timed burst of neuromuscular activity which must have been dispatched from the central nervous system as a pre-formulated message well in advance of the actual landing.

The present experiments were designed to test this conclusion by measuring muscular activity after suddenly and unexpectedly dropping human subjects from various heights above the ground. Presumably, if deceleration were mainly effected by a stretch reflex, the ease of landing would be largely independent of height. However, if a pre-programmed signal was necessary, then the relevant muscular activity would only become effective during landing from falls above a certain height.

METHODS

Eight healthy, young adult subjects took part in this experiment. A strong electromagnet was suspended by means of a block and tackle and the subject grasped a metal handle attached to it (Fig. 1). The individual was then raised off the ground so that the distance from toes to a force-transducing platform (Melvill Jones & Watt, 1971) varied from 2·5 to 20·3 cm. By shutting off the current to the magnet at an unpredictable moment, a quiet, unheralded, and unimpeded drop was obtained. The moment of release was marked by the breaking of a small electric current, passing from the magnet to the handle. Before release, subjects hung with their leg muscles relaxed and toes pointing slightly downwards.

The force exerted by the subject's feet on landing was measured by the previously mentioned transducing platform. The electromyographic (e.m.g.) activity of the gastrocnemius muscle of one leg was recorded using Beckman surface electrodes, located over the upper part of gastrocnemius to avoid interference from soleus. The moment of contact with the platform was confirmed using a microphone placed as close as possible to the landing point.

All results were displayed on a Tektronix type 565 oscilloscope, and recorded on moving film, using a Shackman oscilloscope camera. This record was later projected and enlarged for analysis.

RESULTS

E.m.g. activity

Fig. 2 illustrates the response to falls from two different heights. The first arrow in each record indicates the moment of release from the electromagnet, while the second marks the moment at which the toes first struck the ground, and hence, the earliest possible moment at which a stretch to the gastrocnemius could have commenced. It is seen that the largest part of the e.m.g. activity associated with the landing deceleration was completed before the time required to generate a functionally effective stretch reflex in the same leg muscles (mean FSR time (e.m.g.) = 119·5 msec, S.E. of mean = 3·5 msec), and certainly before the time taken to make the quickest possible voluntary plantar flexion effort to a light tap on the Achilles tendon (mean 163 msec, S.E. of mean = 6·8 msec) (Melvill Jones & Watt, 1971). Indeed, there was often a suggestion that the e.m.g. activity was inhibited at the time when the FSR would have been expected to occur.

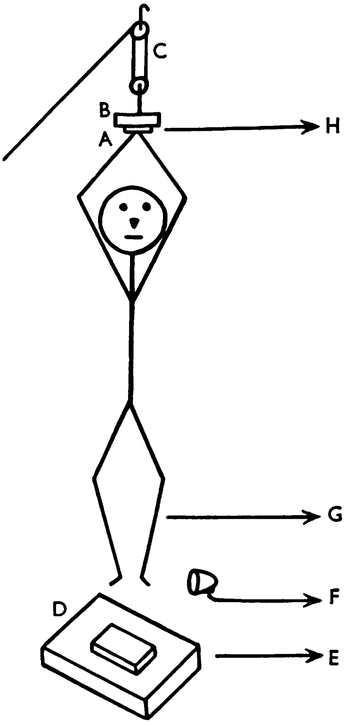

Fig. 1. Diagram of apparatus used in the present experiments. Subjects grasped a handle (A), which could be released from an electromagnet (B) after the individual was lifted above a force-transducing platform (D) by a block and tackle (C). Recorded were: force exerted by feet on landing (E), sound of moment of landing (F), gastrocnemius e.m.g. (G), and, moment of release (H).

Comparison of the two falls illustrated in Fig. 2 also shows that the e.m.g. activity began in both instances about 75 msec after the start of the fall, and it is of interest that this pattern is also mirrored in the tibialis anterior muscle. Fig. 3, which summarizes all results obtained from the eight subjects, illustrates that the interval from the start of the fall to the first detectable surface e.m.g. activity was independent of the height of the fall up to at least 8 in. The mean value for this interval in all subjects was calculated to be 74·2 msec (S.E. of mean = 1·4 msec). This is significantly shorter ($P < 0·001$) than the FSR time or the time taken to make the quickest possible voluntary plantar flexion following a tap to the Achilles tendon.

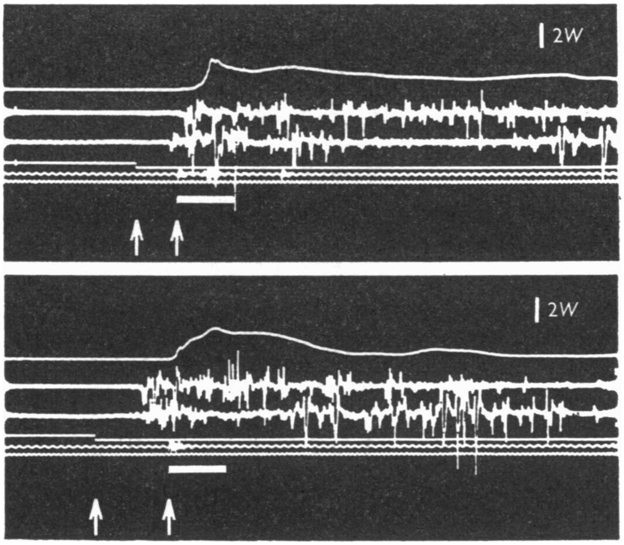

Fig. 2. The effect of landing from an unexpected fall. Two original records demonstrate falls of 6·4 and 17·8 cm. From above down the tracings in each record represent force exerted by the foot on the landing platform, the gastrocnemius e.m.g., the tibialis anterior e.m.g., an electrical signal indicating the moment of release from the electromagnet, the sound of landing (with 60 Hz a.c. superimposed on it) and a 100 Hz time base. In each example, the first arrow indicates the moment of release, and the second the moment of contact. The horizontal line starting at the second arrow indicates the time following contact of the toes during which an FSR could not contribute to the e.m.g. activity in the gastrocnemius muscle. Force build-up is less rapid in the case of the higher fall, and reaches approximately the same maximum value in both falls. E.m.g. activity in both gastrocnemius and tibialis anterior, at both heights of fall, starts about 75 msec after the start of the fall. *W* designates the static weight of the particular subject.

Consequent to the demonstration in Fig. 3 that the first detectable surface e.m.g. activity commences 74·2 msec after the release of the subject from the electromagnet, independent of height, the following becomes evident. First, in falls of less than 75 msec, i.e. of less than 2·8 cm, there will be no e.m.g. activity in the antigravity muscles of the lower leg upon impact. Secondly, given a fastest electrical-mechanical coupling time of 28 msec (S.E. of mean = 1·8 msec), measured in these subjects by comparing surface e.m.g. activity in the gastrocnemius with the force exerted by the ball of the foot during voluntary plantar flexions about the ankle, an effective build-up of gastrocnemius muscle tension would not commence until at least 102·2 msec after the start of a fall, by which time the subject will have travelled downwards some 5·1 cm.

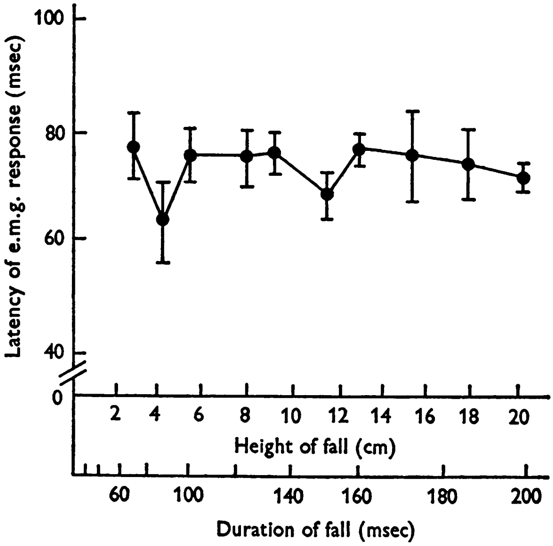

Fig. 3. Summary of results from eight subjects dropped unexpectedly, from 2·5 to 20 cm. The time from the moment of release until the first gastrocnemius e.m.g. activity is plotted against the height of fall and corresponding duration of fall. Each value is an average for all subjects at that height, and is bracketed by 1 S.E. of the mean above, and below. This latency did not change with height, and has an average value for all subjects and experiments of 74·2 msec (S.E. of mean = 1·4 msec, n = 32).

Force

Further examination of Fig. 2 shows that although the total energy required to decelerate the body mass must be less for falls of lower height, the maximum force exerted by the foot during landing from the lower fall was no smaller than that during landing from the higher one. This apparent paradox is accounted for by the fact that the rate of buildup of force was consistently much more rapid on landing from short falls of less than 7·5 cm than from longer falls of more than about 13–15 cm. Thus whereas the deceleration from the 17·8 cm fall in Fig. 2 was brought about by a relatively smooth, prolonged pattern of force development, the corresponding force during deceleration from the 6·4 cm fall developed more abruptly. As already mentioned, this deceleration cannot be attributed to the FSR, since the latter would not begin until at least 120 msec after the onset of muscle stretch occurring at the moment of impact.

The fact that the sharp rise of force in the lower fall consistently occurred synchronously with a *second* sound, and only after 40 msec delay from the moment the toes first touched the ground (first sound), suggests it arose as a result of the heel forcibly striking the ground after passive dorsiflexion of the foot. Indeed, this was confirmed by most subjects in falls of less than 7·5 cm. This would account for the impressive subjective feature that landings from falls of less than 9–13 cm were invariably associated with a most uncomfortable jolt, whereas landings from falls above 15–18 cm were not. Even a drop of 2·5 cm regularly led to a very uncomfortable landing. Presumably when the heel strikes the ground like this, deceleration tends to be imposed as a sudden, jarring impact through the body skeletal structures, whereas a muscularly controlled deceleration such as that associated with the 17·8 cm fall of Fig. 2, when the heel did not touch (one sound only), is relatively smooth and gentle.

DISCUSSION

In a previous paper, Melvill Jones & Watt (1971) showed that the e.m.g. activity associated with landing from a single intended step or jump to the ground began well before the moment of landing, and was completed before a functionally useful stretch reflex (FSR) due to the landing event could have become effective. It was therefore inferred that the muscular control of landing was based upon a pre-programmed neural message, formulated in, and dispatched from, the central nervous system with great precision of timing well before the moment of landing. This conclusion suggests that on landing from an unintended fall any reflex muscular activity resulting from the landing event would occur too late to be of use in decelerating the body mass. The present results confirm this suggestion by demonstrating that unintended falls below about 13 cm (160 msec duration) are always associated with an uncomfortable, jolted, landing and irregular, sharp development of large transient forces transmitted directly through skeletal structures rather than via the antigravity musculature. In fact, the e.m.g. activity often appears to be inhibited at the time when the FSR would have been expected to occur. This may be related to the depression of the tendon jerk response shown by Matthews (1956) in human subjects during sudden falls, and to the strong post-excitatory inhibition of the motoneurone pool shown by Gernandt, Katsuki & Livingston (1957), and later Gernandt & Gilman (1960), following electrical stimulation of the vestibular nerve trunk.

A second, unexpected feature of the results was the constant, short latency e.m.g. response occurring on average 74·2 msec after initiation of the fall, i.e. a sudden transition from a one 'g' to a zero 'g' accelerative state. The facts that this latency was independent of height of fall, that it deviated little from the mean value, and the shortness of its duration compared to a corresponding voluntary response (requiring a minimum of 163 msec from the moment of a light tap to the Achilles tendon until the first detectable surface e.m.g. activity) all point to its being reflex in origin. One might guess it may originate in the otolith organs which must be subjected to a violent, synchronous, transient stimulus at the instant of sudden transition from one to zero 'g' i.e. a very sharp transient of 9·8 m/sec^2.

Thus, the manner in which landing from unexpected falls is controlled by the body musculature is dependent on the height of the fall. Falls requiring less than 102 msec (5·1 cm) do not allow sufficient time for the build-up of any tension in the leg antigravity muscles, with the result that landings produce sharp skeletal jolts. Possibly, this explains the very disrupting and sometimes injurious effect of an unexpected change of step height in a set of stairs, or an unexpected step down an unseen curb. Falls of over 5·1 cm allow the reflex build-up of some muscle tension to protect the body from a jolt, but it is not until sufficient time has elapsed falling (over 191 msec, i.e. 163 msec voluntary response time, plus 28 msec electrical-mechanical coupling time) that a truly comfortable, well controlled landing consistently results. This requires a fall of about 18 cm. Between the fall heights of 5·1 and 18 cm then, only reflex activity, presumably originating in the otolith apparatus, is available to decelerate the body mass, and it is notable that it appears to activate both the antigravity muscles and their antagonists. This latter fact, plus the rather long latency of 74·2 msec, suggests that the response may be mediated via reticulospinal pathways.

In a previous paper (Melvill Jones & Watt, 1971) it was shown that the e.m.g. pattern during repetitive hopping movements differs from that during a step (Fig. 4). During hopping, e.m.g. activity starts later and lasts longer, sufficiently long that is to allow the FSR to contribute to acceleration of the individual upwards into the next hop. It was also noted that each subject had a frequency at which he performed most comfortably. While hopping at that frequency, which averaged 2·06 hops/sec in eight subjects, the time from leaving the ground until the start of the e.m.g. response concerned with the next landing was 69 msec (S.E. of mean = 14·6 msec), a value insignificantly different ($P >$ 0·4) from the dropping reflex latency observed in the present results. At a faster average rate of 2·55 hops/sec, however, this time was found to be 52 msec (S.E. of mean = 9·9 msec) and at a slower rate of 1·6 hops/sec, the delay was 94 msec (S.E. of mean = 13 msec). Both of these values are significantly different ($P < 0{\cdot}01$) from the dropping reflex latency. Excluding purely mechanical factors, one could speculate that at least three main mechanisms contribute to the stereotyped timing of the preferred hopping frequency: a pre-programmed

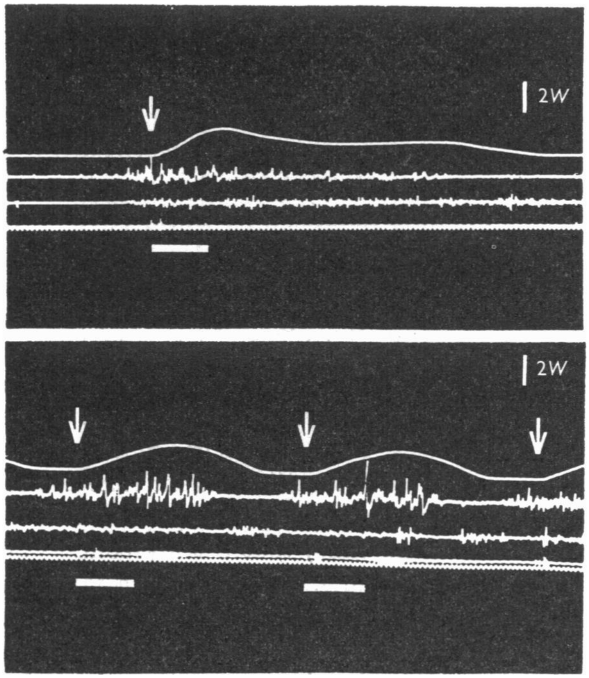

Fig. 4. The e.m.g. response of the gastrocnemius and tibialis anterior muscles and the force exerted simultaneously by the ball of the foot, during a single 25·4 cm step to the ground, and during repetitive hopping at a constant rate. In each example, the tracings represent the force exerted on the landing platform, the gastrocnemius e.m.g., the tibialis anterior e.m.g., the sound of landing and a 100 Hz time base. The arrows in all cases represent the moment the toes make contact with the landing platform. The solid horizontal bar indicates the time after initial contact during which an FSR could not occur. In the case of the 25·4 cm step, e.m.g. activity in both muscles precedes the landing, and most is completed before an FSR could contribute. In repetitive hopping, the e.m.g. activity in gastrocnemius also precedes the landing, but it continues for a longer period of time than in the response to a single step. The tibialis anterior appears to be most active just before the toes leave the ground. The time from leaving the ground until the start of the e.m.g. activity concerned with the next landing is about 50 msec, at this subject's preferred frequency of hopping.

landing, a functional stretch response causing acceleration upwards into the next hop, and a vestibular response to sudden weightlessness (on leaving the ground) to aid in setting the timing and degree of activity of the most appropriate programme for the subsequent landing. Possibly, the most comfortable hopping frequency is the one at which the programmed landing, and the response to sudden weightlessness, coincide, facilitating a motor response at that moment. It may be that a similar process aids in the setting of a preferred frequency of running as well, though this latter frequency tends to be slightly higher than that used for hopping.

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