J. Anat. (1987), 155, pp. 1–5
With 2 figures
Printed in Great Britain

# The unique action of bi-articular muscles in complex movements

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(*Accepted* 16 *January* 1987)

## INTRODUCTION

For understanding the co-ordination of muscles in complex movements, it is of particular interest to know the potential actions of all types of muscles involved. At present the action of muscles that pass over more than one joint is mainly described with respect to movements in the joints that are crossed (Williams & Warwick, 1980; Jensen & Schulz, 1977; MacConaill & Basmajian, 1969). However, Elftman (1939, 1940) hypothesised that bi-articular muscles might play a role in saving energy expenditure. This point has been further elaborated by Grégoire, Veeger, Huijing & Van Ingen Schenau (1984), who showed that the rectus femoris and gastrocnemius muscles are used to transport energy from proximal to distal joints during jumping. If, for example, knee extension is accompanied by plantar flexion while gastrocnemius exerts a large force, power delivered by the knee extensors is used in part for plantar flexion (Grégoire *et al.* 1984).

Recently it has been shown that in a push-off without plantar flexion, as is the case in speed skating, one is not able to fully extend the knee during push off. These results made it a likely assumption that bi-articular muscles can play a unique role in the transformation of rotation in the knee joint into the translation of the body centre of gravity in such a way that this centre of gravity is continuously accelerated during the push-off.

The purpose of this study was to shed more light on this hypothesis by means of an analysis of a vertical jump.

## METHODS

Two-legged counter movement jumps of ten experienced jumpers were filmed (16 mm, 100 frames per second) at approximately right angles to the sagittal plane. Using a motion analyser the positions of the foot (determined by the fifth tarsometatarsal joint and the tuber calcanei), ankle joint (±1 cm anterior to tip of the lateral malleolus), knee joint (joint gap measured at the fibular collateral ligament) and hip joint (greater trochanter) were determined. Ground reaction forces were measured by means of a Kistler force plate. Angles, angular velocities, net moments and forces were calculated according to the procedures described by Grégoire *et al.* (1984). The curves of the subjects were synchronised at the instant of take-off. Mean curves were calculated by averaging the values of the subjects for each frame. The velocity difference between hip and ankle was calculated directly from the coordinates of hip and ankle. Electromyography patterns of vastus lateralis, rectus femoris and both heads of gastrocnemius were recorded by surface electrodes (Beckman). The signals were full wave rectified and low pass filtered (cut off frequency 7·4 Hz; slope: 6 dB/octave). Mean level of electromyographic activity during push-off was determined. The resultant signal was expressed as a percentage of this mean level in order to calculate a mean curve of electromyographic activity for all subjects.

## RESULTS

The mean activity pattern of vastus lateralis and of both heads of gastrocnemius are presented in Figure 1. The activity pattern of rectus femoris is not presented since it resembles the pattern of vastus lateralis to a large extent. Patterns are drawn for the push-off phase only. The onset of this phase is defined as the time from which the velocity of the body centre of gravity is positive. Figure 1 also shows the velocity differences $V_{HA}$ between hip and ankle, $V_{AG}$ between ankle and ground and $V_{HG} = V_{HA} + V_{AG}$ between hip and ground. The velocity difference $V_{HA}$ reaches its maximum value at a mean knee angle of 132°. The curves show that the velocity difference $V_{AG}$ which is mainly due to plantar flexion, is suddenly increased at about 70 ms preceding lift-off. The timing of this increase of $V_{AG}$ is such that the velocity difference between hip and ground can continue to increase despite the decrease of $V_{HA}$.

## DISCUSSION

The maximal velocity difference between hip and ankle appears to be reached at a mean knee angle of 132°. This is an important phenomenon which is due to two constraints:

(*a*) It has been argued before (Ingen Schenau, de Boer & de Groot, 1985) that it is essentially impossible to maintain a positive acceleration of $V_{HA}$ up to full extension. If the knee approaches full extention, $V_{HA}$ will fall to zero independently of the knee extension velocity. The hip can then no longer be removed from the ankle. The transformation of knee angular velocity into the translational velocity difference $V_{HA}$ is less effective the larger the knee angle. This constraint can be described by simple goniometry (Ingen Schenau *et al.* 1985) and is called a geometrical constraint.

(*b*) To prevent hyperextension of the knee, the actual knee angular velocity has to be decelerated to zero velocity at full extension. This can be described as an anatomical constraint.

If this explosive push-off were to have been performed without plantar flexion, the end of the push-off would fall at the knee angle at which $V_{HA}$ reaches its peak value. At that instant the larger body segments, which have achieved a velocity with respect to the ground, would pull the smaller segments from the ground. This would mean that the knee extensors would be able to shorten over a limited range only. The mean angle of deepest knee flexion at the onset of push-off was 82°. From the total possible extension range of 98° (from 82 to 180°), only 50° would then be used to accelerate the position of the hip. However, because of a fast plantar flexion (mean peak value: 15 rad $s^{-1}$) the hip can be accelerated up to 25 ms before lift-off. This plantar flexion appears to be reinforced by activation of gastrocnemius. Figure 1 shows a time interval between the increase of activation of the gastrocnemius and the increase of $V_{AG}$. This phase lag will mainly be caused by an electro-mechanical delay of 30–50 ms (Komi, 1979) and by the catapult-like action of the tendo calcaneus (Achilles tendon) (Alexander & Bennet Clark, 1977; Hof, Geelen & van den Berg, 1983; Bobbert, Huijing & van Ingen Schenau, 1986*a–c*). Given the geometrical and anatomical

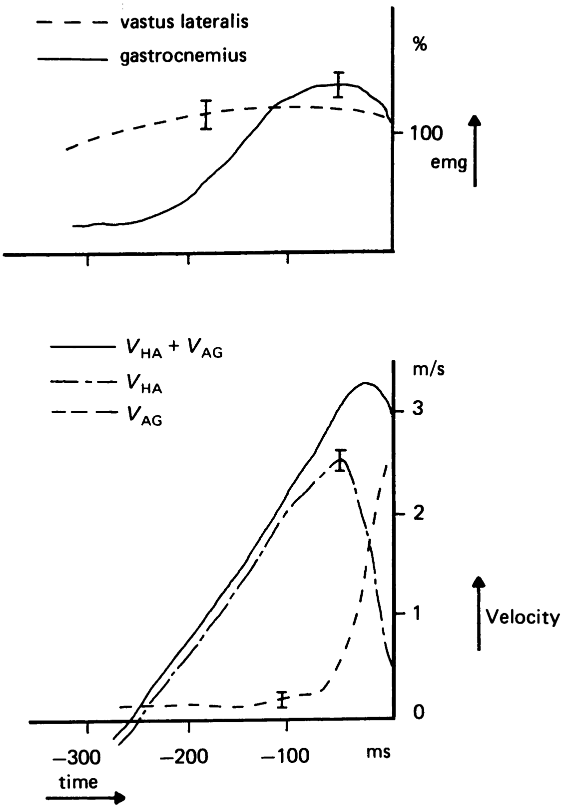

Fig. 1. Electromyographic patterns of the vastus lateralis muscle and mean of both heads of the gastrocnemius. Velocity differences $V_{HA}$ between hip and ankle joint, $V_{AG}$ between ankle joint and ground and $V_{HA} + V_{AG}$. Time is expressed in ms preceding lift-off. It should be noted that a difference of 30% in peak velocity between $V_{HA}$ and $V_{HA} + V_{AG}$ corresponds to a difference in work output of approximately 70%.

constraints it seems obvious that the action of the gastrocnemius is meant to compensate for the inevitable decrease of $V_{HA}$ at the end of the push-off. Since the angular velocity in the knee joint has to be decelerated to zero to avoid over-extension of the knee, the bi-articular gastrocnemius muscle plays a unique role in the last phase of the push-off. It opposes knee extension and reinforces plantar flexion. If only mono-articular muscles were involved, a continuing contraction of the knee extensors would be useless. Power would be dissipated into heat in a necessary eccentric contraction of a mono-articular knee flexor. Moreover plantar flexion would have to be performed by plantar flexors only, at a high contraction velocity. The bi-articular muscle gastrocnemius, however, allows the knee extensors to continue to contract and deliver power. This power is not used for further increase of $V_{HA}$, but is used for plantar flexion: the knee extensors pull on the calcaneus as a result of the action of the gastrocnemius.

It was reported previously (Grégoire *et al.* 1984) that rectus femoris also contributes to a proximodistal energy transport. Interpreted in terms of the constraints described here concerning the transformation of rotations in joints into translation of the centre of gravity, the significance of this transport mechanism becomes convincing.

Figure 2 shows a schematic representation of the muscles investigated. The jump is

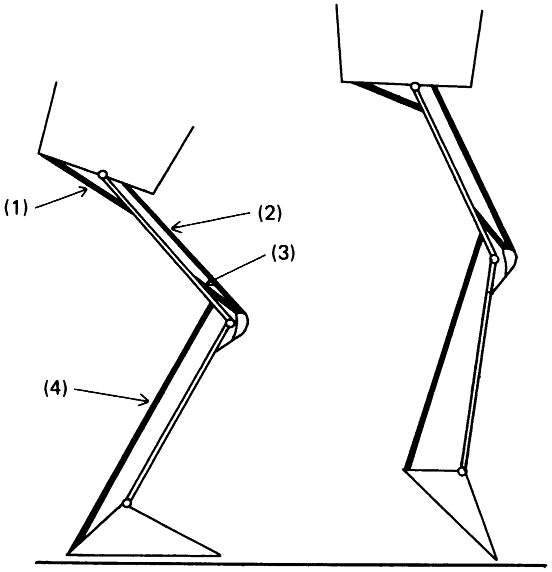

Fig. 2. Schematic representation of muscles (and muscle groups) which are known to contribute to the high mean power output of 2000–3000 watts per ankle found in plantar flexion during jumping. The mono-articular muscle gluteus maximus (1) and the vasti muscles (3) can deliver power until the end of push-off since the opposing effects of the rectus femoris (2) and the gastrocnemius (4) are large enough to result in net flexing torques which decelerate the angular velocities of the hip and knee extension respectively.

initiated by an acceleration of the (relatively heavy) trunk as a result of activation of gluteus maximus and due to a short intensive burst of activity of the hamstrings (Grégoire *et al.* 1984). The termination of the hamstring activity allows the knee extensors to extend the knee joint. Because of the geometrical constraint the effect of the angular velocity of the trunk on the velocity of the centre of gravity decreases. Further acceleration of this angular velocity by gluteus maximus is opposed by rectus femoris. As a consequence gluteus maximus can continue to deliver power since this power is used for knee extension and plantar flexion by the tendinous actions of both rectus femoris and gastrocnemius. At present this mechanism can only be described qualitatively on the basis of activity level and contraction velocities of muscles and on the basis of net force, torque and power-time histories in the joints measured using methods previously described (Grégoire *et al.* 1984). Nevertheless it can be concluded that (at least) all muscles indicated in Figure 2 contribute to the high power output (up to 2000–3000 watts per ankle) found during plantar flexion in the last phase of the push-off. This optimal use of the capabilities of all these muscles would be impossible if man had mono-articular muscles only. The general character of the constraints discussed for human skating and jumping makes it most likely that this last conclusion is also true for other running, jumping and hopping organisms. Hopping and running also show a simultaneous knee extension and plantar flexion (Winter, 1983). Moreover, it can be deduced from studies on locomotion of cats that knee and ankle angles have a more or less similar pattern during push-off in galloping and trotting as the patterns shown in the present paper (Engberg & Lundberg, 1969; Wetzel Atwater & Stuart, 1976). Even in the walking of cats deceleration of the knee angle at the end of the stance phase appears to be compensated by plantar flexion since the distance between hip and toe is continuously increased (Wetzel *et al.* 1976).

It is concluded that bi-articular muscles have a unique function in the transformation of rotations in joints to translation of the body.

## SUMMARY

Actions of muscles that pass over more than one joint are mainly described with respect to movements in the joints that are crossed. In a previous study of push-off without plantar flexion it was shown that the transformation of knee angular velocity into translation of the body is constrained by the fact that velocity difference between hip and ankle has to reach its peak value a long time before the knee is extended. The present study was meant to test the hypothesis that the action of the gastrocnemius can be understood in the light of this constraint.

Vertical jumps of ten subjects were analysed cinematographically. Electromyographic signals were derived from knee extensors and plantar flexors simultaneously. The results show that the peak velocity difference between hip and ankle is reached at a mean knee angle of 132°. At that instant a rapid plantar flexion starts, reinforced by a strong increase of activation of gastrocnemius. It is suggested that the bi-articular character of the gastrocnemius muscle enables the knee extensors to continue to deliver work which is transported to the ankle where it is used for plantar flexion. This optimal use of the capabilities of proximally located muscles would not be possible if man had mono-articular muscles only.

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