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In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump

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Abstract An optic fibre method was used to measure in humans in vivo Achilles (ATF) and patellar tendon forces (PTF) during submaximal squat jumps (SJ) and counter movement jumps (CMJ). Normal two-legged jumps on a force plate and one-legged jumps on a sledge apparatus were made by four volunteers. Kinetics, kinematics, and muscle activity from seven muscles were recorded. The loading patterns of the tendomuscular system differed among the jumping conditions, but were similar when the jumping height was varied. Peak PTF were greater than ATF in each condition. In contrast to earlier simulation studies it was observed that tendomuscular force could continue to increase during the shortening of muscle-tendon unit in CMJ. The concentric tendomuscular output was related to the force at the end of the stretching phase while the enhancement of the output in CMJ compared to SJ could not be explained by increases in muscle activity. The stretching phase in CMJ was characterised by little or no electromyogram activity. Therefore, the role of active stretch in creating beneficial conditions for the utilisation of elastic energy in muscle was only minor in these submaximal performances. The modelling, as used in the present study, showed, however, that tendon underwent a stretch-shortening cycle, thus having potential for elastic energy storage and utilisation. In general, the interaction between muscle and tendon components may be organised in a manner that takes advantage of the basic properties of muscle at given submaximal and variable activity levels of normal human locomotion.

Key words Muscle mechanics · Tendon force · Muscle-tendon interaction · Power · Optic fibre

Introduction

In human movement studies standing jumps with and without a counter movement have been widely explored both experimentally (e.g. Asmussen and Bonde-Petersen 1974; Komi and Bosco 1978; Gollihofer et al. 1992; Fukashiro et al. 1995) and by computer simulation (e.g. Pandy and Zajac 1991; Bobbert et al. 1996). The performance itself, with regard to jumping height and movement kinematics, as well as to different aspects of neuromuscular function of the muscles involved in the tasks has been covered in the literature. For example, enhanced muscular performance during a counter movement jump (CMJ) as compared to a squat jump (SJ) has been attributed to increased myoelectrical activity (Bosco et al. 1982), recoil of elastic energy (Komi and Bosco 1978; Fukashiro et al. 1995), the time available for force development (Bobbert et al. 1996) and a high force at the end of the stretching phase (Zajac 1993). From these factors, recoil of elastic energy has been shown to be very important in economising muscular performance both in animal (Alexander and Vernon 1975; Morgan et al. 1978) and human locomotion (Thys et al. 1975). In accordance with these observations, Anderson and Pandy (1993) suggested that the elastic tissues improve the efficiency rather than jumping height of CMJ compared to SJ.

The complex multijoint nature of standing jumps raises difficulties when the function of individual muscles or muscle groups are of interest. Muscle modelling with inverse solutions has provided net joint moments (Fukashiro and Komi 1987) and estimated muscle forces
(Bobbert et al. 1986). While forward dynamics models rely on measured neuromuscular signals (Zajac 1993) experimental muscle force data are scarce due to the methodological challenges involved. If muscle forces can be directly recorded, one can avoid the often inaccurate estimation of changes in moment arms of a muscle during locomotion and its effect on calculated muscle forces. Furthermore, modelling studies usually simulate optimal performance while little is known about submaximal movements where one may observe individually different movement strategies with variability in activation patterns and movement kinematics, which make calculation of forces produced by a muscle group or a single muscle even more complex.

In the course of developing a force transducer for human studies, animal experiments provided a basis for applying the buckle force transducer in recording Achilles tendon forces in men (Komi et al. 1987). Later, the method was used to measure human tendomuscular forces in natural movements such as walking, running, cycling and jumping (Komi 1990; Gregor et al. 1991; Komi et al. 1992; Fukushima et al. 1993, 1995). Recent development of an optic fibre technique (Komi et al. 1996) has opened up new possibilities for less invasive tendon force measurements in routine experiments (Finni et al. 1998). The fact that the insertion of an optic fibre is quick and virtually painless is a clear advantage over the more invasive buckle-type transducer technique. The optic fibre is inserted through the entire cross-section of the tendon and the tendon deformation during locomotion compresses the optic fibre inside the tendon. It has been shown that this compression can then be calibrated to represent the in vivo tendomuscular force (Komi et al. 1996).

In the present study, the optic fibre method was used to study triceps surae (TS) and quadriceps femoris (QF) muscle loading during SJ and CMJ. Different levels of submaximal jumping performance were used to examine how the output of TS and QF muscles is modulated to achieve greater jumping height. Instantaneous force-length and force-velocity relationships together with muscle activation are presented to examine the nature of muscle action and the relationship between muscle input and output. As length changes in the complete muscle-tendon complex may not correspond to the changes at the muscle fibre level, Achilles tendon and soleus muscle compartment interaction is also examined using modelling techniques.

Methods

Subjects

Four healthy subjects volunteered for this study [three women and one man whose body masses and heights were mean 63 (SD ± 3) kg, mean 167 (SD ± 4) cm, and 90 kg, 181 cm, respectively]. The subjects were informed of all the risks associated with the study and gave their written consent to participate. The subjects were free to stop the experiment at will. The recommendations contained in the Declaration of Helsinki were followed and the Ethics Committee of the Central Hospital of Central Finland approved the study.

Experiment protocol

Prior to the day of measurement the subjects were introduced to the jumping activities to be performed on the sledge apparatus that has previously been described (Kaneko et al. 1984) and on the force plate. Using the sledge the joint movements could easily be controlled and the contribution of the hip joint was limited because the subject’s upper body was secured to the back of the chair of the apparatus. The purpose of these measurements was also to evaluate possible alterations in jumping performance due to the insertion of the optic fibre. Visual comparison of the electromyogram (EMG) and ground reaction force patterns showed that the presence of the optic fibre in the tendon did not cause any disturbances.

Isometric maximal voluntary ankle plantarflexions (90° angle) were performed on the ankle ergometer that has been described previously by Kyröläinen and Komi (1994) where torque around the rotational axes of the pedal was measured by a piezoelectric strain transducer (Kistler transducer). The pedal was equipped with a strain gauge and the torque applied to the pedal was converted to force under the point of force application. The distance from a 1-cm-wide bar under the first metatarsal head to the rotational axis was measured as the length of the pedal lever arm. Isometric maximal voluntary extensions of the knee (120°) were measured using the knee ergometer as it has been described by Komi et al. (1999, in press). In this machine the test rig was equipped with a strain gauge and the lever arm length could be read from an inbuilt ruler. The same knee and ankle ergometer settings were used in the calibration of the optic fibre force transducer.

On the measurement day, after the optic fibres had been inserted, the subjects made one-legged jumps on the sledge apparatus that had an inclination of 20° from the horizontal position. With one-legged jumps any possible bilateral differences could be avoided. Furthermore, the hip joint angular displacement was reduced and easily controlled compared to normal standing jumps. Two to five SJ and CMJ were performed with increasing effort, thus jumping a little higher each time. The amplitude of the sledge movement in each jump was predetermined and the subjects were provided with visual feedback of their performances from a monitor in front of them. On the force plate, SJ and CMJ were repeated as normal two-legged jumps.

Optic fibre technique

The transmitter-receiver unit used in the optic fibre method contained a light emitting diode and a PIN photodiode receiver (Hewlett Packard, USA), the light signal (wavelength 820 nm) travelled in the core of the plastic optic fibre and returned to the unit for conversion into an analogue signal which was sent telemetrically to the recording computer. The use of optic fibre as a transducer for tendomuscular forces is based on light intensity modulation. Tendomuscular loading has been shown to develop tensile stress within the tendon fibres (Butler et al. 1978). This stress compresses the plastic optic fibre inside the tendon. A linear relationship has been reported between an increasing loading of the tendon and the intensity of the light passing through the optic fibre (Komi et al. 1996; Arndt et al. 1998) even in maximal voluntary contractions (MVC; Finni et al. 1998).

The subjects arrived at the laboratory at least 1 h before the insertion of the optic fibre took place. First, a pad covered with an anaesthetic cream containing lidocaine-prilocaine was placed over the skin of the calcaneal and patellar tendons of the right leg and kept in place for at least 1 h. With the subject lying prone and with the ankle angle secured at 90°, a hollow 19 gauge needle was passed through the right Achilles tendon 2–3 cm proximal to the calcaneus. The direction of the needle was perpendicular to the tendon. Aseptic conditions were ensured during the insertion procedure. The optic fibre, sterilised using ethylene oxide at 37 °C, was then passed through the needle. By removing the needle the fibre