Intermuscular co-ordination during fast contact control leg tasks in man

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Abstract

From previous inverse dynamic analyses of human leg extensions, it was hypothesized that the underlying processes for the activation of mono- and biarticular muscles are different; the mono-articular muscles being activated when they shortened, whereas the biarticular muscles appeared responsible for the control of the external force direction. In the present study, experiments were performed on a dynamometer which was especially developed to test this hypothesis. Subjects had to exert different prescribed force vectors on a moving force-plate during leg extension, which they had intensively practised prior to the actual experiments. Of each trial, position, force and EMG activity were recorded. Net joint torques were calculated by the method of inverse dynamics and related to the EMG-patterns of the mono- and biarticular upper leg muscles to reveal whether the previously observed different roles in contact tasks might constitute a general principle in motor control. The results showed that although the action of the biarticular m. rectus femoris and hamstrings muscles was consistent in controlling the direction of the external force, the actions of the mono-articular muscles did not agree with their hypothesized role as simple work generators. The generalizability of a different control for mono-and biarticular muscles could thus not be confirmed for these tasks. They might rather reflect one out of more available strategies the CNS can use to control different contact control tasks.

Keywords: Biarticular leg muscle; Force control; Motor control; Electromyography

1. Introduction

Most goal-directed human and animal motions involve multiple joints in which specific combinations of joint torques are necessary to achieve the required segmental accelerations and the appropriate direction and magnitude of the force on the environment. From a mathematical point of view, there is a considerable number of ways in which muscles may interact to generate a specific movement. However, results from experimental studies using electromyography (EMG) or direct muscle force measurements indicate that even the most complex, i.e. multi-joint, movements are performed in a stereotyped way (e.g., [9,12,28]). To understand the backgrounds of these stereotyped patterns of intermuscular coordination, a number of modelling and experimental approaches have been used to study the distribution of the forces between muscles. The general purpose of these studies was to reveal (biomechani-
To test the hypothesized different roles for mono- and biarticular muscles experiments were done in which force direction had to be controlled in (quasi-)static leg extensions [6,16]. However, in comparison to cycling, the role of the mono-articular muscles was less clear in these studies, possibly due to the (quasi-)static character of those experiments. Experiments under dynamic conditions might reveal more clearly the proposed differences in control for mono- and biarticular muscles. For this purpose, a dynamometer (Fig. 1) is used to test the hypothesis whether a general organizational principle underlies a more or less independent control of mono- and biarticular muscles. With the tasks on the dynamometer (contact control tasks), in which the subjects had to exert a force in prescribed directions, it is expected that the different force directions would be realized by changes in activation of the biarticular muscles only. The tasks were executed cyclically at relatively high speed. The aim of the present study was to examine the roles of the mono- and biarticular muscles during these so-called fast contact control leg tasks (CCTs).

2. Materials and methods

2.1. Dynamometer

In the dynamometer used for the experiments, a force-plate is moved in a straight line along a rail of about 1 m. The rail could be mechanically rotated about an axis at the lower side of the rail, as well as translated over a double bar at the bottom of the frame (Fig. 1). This allowed for the adjustments of different movement directions of the force-plate.

The force-plate runs over a ball-rotation spindle via a metal mounting fixture. This spindle is attached by cog-wheels to a servo-motor (SEM, MT3OU4-36, London, UK) which is controlled by a motion control software package (GALIL DMC-710, Sunnyvale, CA, USA). Strain gauges built in the force-plate were used to measure the exerted force in the sagittal plane.

2.2. Subjects and experimental procedure

Three male and two female subjects (age: 25.4 ± 3.6 years; height: 1.79 ± 0.1 m; weight 71.1 ± 6.5 kg) participated in the experiments. Informed consent was obtained from all subjects. During two months prior to the actual experiments, all subjects participated twice a week, in intensive training sessions of 1 h, in which they practiced the required tasks.

Subjects were first placed in a reference position, while sitting on the bike-saddle with their right foot on the force-plate (Fig. 1). In this reference position the hip joint was flexed 115 degrees and the knee joint was set at 100 degrees of flexion (Fig. 2). During the CCTs, subjects had to exert a force in a prescribed direction with a constant magnitude, while the force-plate moved five times downwards and upwards with a velocity of 40 cm s⁻¹, starting at 17 cm above until 17 cm below the reference position and vice versa. The subjects were instructed to exert the prescribed force vector while the force-plate moved downwards and hold the force magnitude and direction as constant as possible during the whole movement. The magnitude of the force differed for the male and female subjects and was set at 300 and 200 N respectively. On-line feedback of the direction and magnitude of the required and the actual reaction force was presented on a computer screen which was placed in front of the subjects. No movements of the foot relative to the force-plate were allowed. Force directions ranged from 45 up to 135 degrees with intervals of 15 degrees (Fig. 2). All seven force directions were executed in each of three different positions of the rail and force-plate, indicated as 0 (perpendicular to the ground), −15 degrees (forward tilted) and 15 degrees (backwards tilted) (Fig. 2).
For each protocol, computer generated audible signals were used to indicate the start of the movement period and the end of the trial. These signals were simultaneously recorded as block pulses and were used for synchronization. During each trial, joint position and reaction force were recorded and muscle activation was registered by means of EMG.

2.3. Position and force

Retro-reflective markers (diameter 13 mm) placed on the skin corresponded with the fifth metatarsophalangeal joint, heel, lateral malleolus, knee joint (on the lateral collateral ligament at the height of the knee cleft), greater trochanter, top of iliac crest and neck (at the height of fifth cervical vertebra). Two landmarks were placed on the force-plate and three on the dynamometer frame as a reference orthogonal coordinate system. Joint positions of the leg in the sagittal plane were collected at 60 Hz using a motion analysis software system (VICON, Oxford Metrics, Oxford, UK). Four camera positions were applied in order to get accurate cartesian coordinates of the landmarks. Special attention was paid to minimize reflections, which could give rise to false marker positions, using black curtains and paint. With the VICON-system, 3-D coordinates are calculated. After proper scaling, the absolute coordinates of the anatomical landmarks in the sagittal plane were obtained, which were subsequently low pass filtered (Butterworth 2nd order, bi-directional of a 5-points approximation, cutoff frequency 2 Hz). This low cutoff frequency was chosen in order to minimize quantisation noise and is appropriate in these isokinetic movements since the joint angles and their derivatives appear not to contain higher frequencies than 1 Hz. The coordinates of the landmarks defined four body segments: foot, lower leg, upper leg and the upper body. Joint angles as well as joint angular velocities were calculated (Lanczos, 5-point differentiation filter, [18]). To determine the positions of the mass centers of the different body segments, the coordinates were combined with anthropometric measurements of each subject and data from Clauser et al. [4] and Winter [31].

Vertical and fore–aft components of the reaction force of the right foot were recorded by means of strain gauges built in a force-plate. The analog force signals were amplified, low-pass filtered (70 Hz, 4th order, 24 dB/oct) and sampled (300 Hz, 12 bits) by MONSTIM. Simultaneously, the force signals were processed by a computer to generate visual feedback of the force vector for the subject. The force direction perpendicular on the force-plate was indicated as 90 degrees and plotted as a vertical line. Of the required force vector, both magnitude and direction were indicated with deviation margins of ±6%. From the distribution of the separated force components measured by the force-plate, the center of pressure of the force vector was calculated. Combined with the points of reference of the position data, the center of application was related to the position of the foot.

Newtonian equations of motion were applied to a linked segment model of the human body in order to calculate the net torques about the hip, knee and ankle joints [7]. Extension torques were defined as positive.

2.4. Electromyography

Electromyographic activity was recorded (DISAS type 15C01, Skovlunde, Denmark) from the following leg muscles: m. gluteus maximus, m. rectus femoris, m. semitendinosus, m. biceps femoris c.longum., m. vastus medialis., m. vastus lateralis. EMG was obtained using bipolar Ag–AgCl surface electrodes (MediTrace type: ECE 1081; lead-off area 0.81 cm², center-to-center electrode distance 2.5 cm) placed on the muscle bellies after standard skin preparations [1]. EMG signals were amplified and sampled (600 Hz) on-line by the VICON-system after band-pass filtering (20–200 Hz). The EMG signals were plotted on a writer (Gould ES 1000, France) for visual inspection during the experiment.

Off-line analysis of the EMG signals included rectifying, low-pass filtering (Butterworth 2nd order, zero phase lag through bi-directional application of a fifth approximation, cutoff frequency 2 Hz) and normalizing to 100% of the SIC values. Values of these standard isometric contractions (SIC) for each muscle group were obtained prior to the actual experiments by the methods described in Jacobs and Ingen Schenau [16]. SIC values were taken as the mean value of the rectified curve for a period of 1 s in which the activation level was stable. The SIC-tests were also used as a functional test to identify possible cross-talk as was recommended by Winter et al. [32].

2.5. Muscle length changes

Joint angle changes during a foot displacement of 20 cm (±10 cm relative to the reference position) in the direction of the movement and information of total muscle length (L_m) as a function of joint angle(s) were used to calculate the length changes (∆L_m) for each muscle for each trial. Positive values indicate a muscle shortening. In order to determine the muscle length as a percentage of segment length, a database of coefficients, derived from various studies, was used. Details can be found in Jacobs and Ingen Schenau [16].

2.6. Treatment of data

EMG, position and force data were synchronized by the pulses, which also generated the audible (cue) signals. For each task, the mean value of net torques and EMG, calculated over a distinct period for each of the two last cycles, were used for further analysis. The mean data were derived from the period for which the knee angle was
within 5 degrees of the reference position during the downward movement. These datapoints were subsequently averaged for all subjects at corresponding tasks.

3. Results

3.1. Task performance

The tasks were performed with high accuracy by all subjects. A comparison between the prescribed force direction and the actual direction of the force as exerted by all subjects is shown in Fig. 3 for each subject. The mean values with the standard deviation (between parentheses) of the each force direction are shown at the inset.

3.2. Net torques and electromyography

The mean EMG-values of all subjects, expressed as a percentage of the SIC value are shown in Fig. 4. The EMG-data are plotted as a function of the net torques about the joints that are crossed by the muscle. Fig. 4 shows that the activity of the gluteus maximus is low at negative (flexion) hip torques, whereas at higher hip extending net torques, the activity of the gluteus maximus increases until about 50% of SIC. Also for the mono-articular vasti muscles an increase of about 60% is seen when they can contribute to the extending knee torques. It is noteworthy that the mono-articular knee extensors are activated (until about 20% of SIC) at negative knee torques as well.

Since the biarticular muscles cross two joints over which they have a simultaneous effect, the EMG data are plotted against the combination of these torques, defined as the net torque difference between knee and hip ($T_k - T_h$). As a consequence, a combination of hip extension and knee flexion results in a negative $T_k - T_h$ difference, whereas a positive difference originates from the opposite
Fig. 5. The activity difference between the hamstrings and rectus femoris for all tasks as a function of the net torque difference \((T_h - T_k)\). Mean EMG data of all subjects \((n = 5)\) are shown with the fitted line. The inset shows the correlation coefficient for the two variables.

A combination of the data points of the biarticular muscles in Fig. 4 is made by subtracting the hamstrings activity from that of the rectus, denoted as RF-HAM. This activity difference is shown in Fig. 5 as a function of net torque difference \((T_h - T_k)\). A remarkably strong relationship between the activity difference RF-HAM and torque difference is found. The mean \((\pm S.D.)\) correlation coefficient was 0.986 \((\pm .004)\).

3.3. Net torques, EMG and muscle length changes

Three different movement directions were used in the experiments. During the movement, the length of the muscles changes as a result of the angular changes in the joints. Since the trajectory of the foot is fixed for each movement direction, the angular changes of the joints are similar irrespective of the executed force directions. For all muscles, three different combinations of muscle length changes \((\Delta L_m)\) are present. In Fig. 6, the mean EMG data of each muscle are plotted as a function of the muscle length changes \((\Delta L_m)\) for each movement direction. In these plots, positive values indicate muscle shortening. The radius of the circles around each datapoint corresponded to the magnitude of required net torque \((T_h\) or \(T_k)\) or net torque difference \((T_h - T_k)\) for that condition.
Filled circles indicate negative torque values. Fitted regression lines demonstrate the relation between the activity level and the amount of muscle shortening.

For the mono-articular muscles, m. gluteus maximus and mm. vasti and for the biarticular m. rectus femoris, an increase of EMG activity is found with increasing net extending torques and increasing muscle shortening. For the imposed movements, only the biarticular hamstrings are lengthening, which occurred in direction 15° of the movement. With larger negative values of $\Delta L_{oi}$, the EMG activity of this muscle group decreases. However, when comparing circles with equal radius at different $\Delta L_{oi}$ values, it is clear that there is only a weak relationship between the length changes and the EMG-activity for both the biarticular as well as the mono-articular muscles.

4. Discussion

4.1. Variability

In order to test the generalizability of the hypothesis that mono-articular muscles are mainly activated when they can contribute to work output and biarticular muscles are uniquely responsible for the direction of the force, indicating different roles in the control of force and position, subjects were asked to perform fast CCTs on a dynamometer. First, it is discussed whether the subjects performed the tasks in a similar way. According to Fig. 3, all subjects performed the experimental tasks quite accurately. The control of force direction results directly from a combination of net torques about the joints, which are a function of muscle activation. The EMG data of the upper leg muscles (Fig. 4) showed that all subjects performed the task in a remarkably similar manner, despite the redundant set of muscles. This most likely points at constraints which lead the subjects to a stereotyped intermuscular coordination to accomplish these tasks. On the basis of the present results, it is not clear what type of constraining mechanism may have led to this highly stereotyped pattern of muscle coordination. Obviously, the results show that the activation of mono- and biarticular muscles is similar in the present CCTs. The question thus arises to what extent this can be explained as an exception of a more general principle or as evidence against the hypothesized neural constraints suggested in previous studies [13–15].

4.2. Is the control of mono- and biarticular muscles based on different organizational processes?

From previous analyses of cycling, running and static leg tasks, it was hypothesized that the biarticular muscles, rectus femoris and hamstrings are uniquely responsible for the control of the force direction on the pedal, allowing this force to do work on the pedal [13,15,16]. For the fast CCTs in the present study, the biarticular upper leg muscles again showed a strong reciprocal pattern of activity as a function of the required net torques. Given the largely noisy character of the electrophysiological data, the mean correlation coefficient of 0.986, describing the relationship between the length torque difference of knee and hip ($T_L - T_{k}$) and the RF-HAM activity difference is even remarkably high. Apparently, this reciprocal behavior played an important role in the distribution of the net torques about hip and knee, hence in the control of the direction of the external force.

However, if the control of the force direction were to be uniquely tuned by the biarticular muscles, the activity of the mono-articular muscles should remain constant, irrespective of the required net torques. This was not confirmed in the present study. Fig. 4 shows that the activity of both the mono- and biarticular muscles increase with increasing net torque. This means that changes in the activity of the mono-articular muscles also have their effect on the magnitude of the net torques and hence on the direction of the external force. Clearly, the high correlation coefficient mentioned for the biarticular muscles, combined with the strong relationships between the joint torques and the activity of the mono-articular muscles can only be explained by assuming a common input of the motoneurons of both types of muscles in this task. This appears to be in strong contrast to what was found previously [13,15].

Moreover, in the stereotyped performance of the dynamometer tasks, the activation of the mono-articular muscles did not solely coincide with the amount of muscle shortening, as would be expected according to the proposed hypothesis. Both the biarticular as well as the monoarticular muscle activity related to the amount of muscle length changes (see Fig. 6). In comparison to the observations in cycling and running, the different roles between mono- and biarticular muscles are thus considerably less pronounced.

The results of this study can be judged as evidence against the presence of a neural constraint of distinctly different control of mono- and biarticular muscles as a general organizational principle. Whether one should propose an alternative general control principle or constraint, which can explain the activation patterns of all CCTs, or that the observed coordination of the present tasks should be judged as an additional available strategy of the CNS is not clear. To refer to the first point, an alternative candidate might be found in the implications of the proposed hypothesis, namely that energy wasting eccentric contractions are minimized [12,25,29]. According to this criterion of minimization of negative muscle power, muscles are not classified to the number of joints they cross, since both mono-articular as well as biarticular muscles are uniquely suitable to perform a specific task with high efficiency [17].

The second option mentioned above is to assume that the CNS has the possibility to use a different strategy.
where not only the biarticular muscles but also the mono-
articular muscles control the distribution of net torque
about the joints. This is for example supported by the
present observation that for the mono-articular muscles
only a weak relationship exists between muscle activation
and the extent to which these muscles can contribute to
external work; i.e., the amount of muscle shortening, which
is in sharp contrast to the actions found in previous studies
(e.g. [15]). Also the finding that the relation between
muscle activation and joint torque is already present at
relatively low joint torques (see Fig. 4), whereas such a
relation can be completely absent in comparable joint po-
positions and external forces in cycling and running, di-
 rects to the use of different strategies rather than under-
standing muscle activation patterns of CCTs by assuming
some umbrella organizational principle or constraint.

As argued before [14], the results of several neurophysi-
ological studies about innate automatic, centrally driven
rhythmic movements as (fictive) locomotion, scratching
or paw shaking and as well as observations from analyses
on reflex control did seem to point to differential neural
constraints which realize a distinct control for mono- or
biarticular muscles [2,3,8,10,11,21–24,30]. The differences
in actions of mono- and biarticular muscles during these
innate automatic movements might be organized on the
basis of circuitries, such as propriospinal networks located
in phylogenetically older parts of the CNS or by younger
structures influenced by genetically coded ‘value systems’
as advocated by Sporns and Edelman [26]. Comparable
arguments can be formulated to explain different organiza-
tions in the control of mono- and biarticular muscles in
fast responses to sudden disturbances [19,20]. The present
results however, demonstrate that, at least in man, other
strategies can be used as well.

It might well be that this different strategy is mainly
induced by the instruction to realize a particular external
force vector which is prescribed and controlled by visual
information. This visual force feedback is distinctly differ-
et from the type of feedback (e.g. fatigue) and goal of the
movement as for example in locomotion. These considera-
tions are also in line with the findings of Tax et al. [27]
that the motor unit behavior of arm muscles depended on
the type of instruction, which determines the initial goal
(movement or force).

However, finally it should be noted that at present the
results of this and previous studies to human CCTs are not
sufficient to formulate decisive arguments against Kuo’s
statement [17] that the CNS does not have any a priori
knowledge of the existence of mono- and biarticular mus-
cles at all.

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