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Lower Extremity Muscle Function During Ergometer Rowing

by

Yves D. Fortin

Thesis submitted to
the School of Graduate Studies and Research
in partial fulfilment of the requirements for the
Master of Science degree in Kinanthropology

Université d'Ottawa/Ottawa University

Ottawa, Ontario, 1994

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Abstract

The purpose of this study was to determine the functional role of six prominent leg muscles during knee extension. Changes in muscle-tendon length and EMG activity were looked at in conjunction with the results from an inverse dynamics analysis. The muscles investigated were the monoarticular vastus lateralis, soleus, gluteus maximus and the biarticular biceps femoris, rectus femoris and gastrocnemius. Four female and five male elite rowers performed on a Gjessing rowing ergometer while kinematic information was recorded on cinefilm. The force applied to the stretcher, the force applied to the oar handle and the EMG activity were sampled simultaneously. Through inverse dynamics, net moments of force at the ankle, knee and hip joints and powers from these moments were computed for one drive.

The results showed a difference in the use of knee extensors by female and male rowers. For the females, the power produced originated exclusively from the hip extensors. This contrasts with the results obtained from the male subjects where power was produced by hip and knee extensors. Plausible explanations include differences in anatomical structures between both sexes (skeletal dimensions, tendon attachments location, muscle mass distribution), differences in rowing technique and deficiency in the knee extensor strength.

Paradoxical activity appeared to take place in the recruitment of the biarticular gastrocnemius and biceps femoris during the extension of the knee. More intriguing was the detection of paradoxical activity from the action of m. rectus femoris at the hip which it seemed to extend.

Keywords: *muscle function, biarticular muscle, two-joint muscles, knee extension.*

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Introduction

In humans, movement is created from a series of events taking place in the muscle. The contraction of skeletal muscle causes bones to rotate about a common centre of rotation within a joint. In the most simplistic situation, two muscles, one muscle on each side of the joint, would suffice to cause flexion and extension about that articulation. In the majority of joints, however, more than one muscle is present on each side of the joint. Furthermore, some muscles cross more than one joint which complicates the assessment of their contribution to a given movement. Muscles that span over two joints have been labelled biarticular, two-joint or double-joint. Muscles crossing two or more joints are considered polyarticular or multi-joint muscles.

To analyze the motion of a robot, a force dynamometer could be attached to each actuator to monitor its contribution to the motion. Nonetheless, even though some researchers have developed methods to attach force transducers (strain-gauges for instance) directly to tendons (An, Berglund, Cooney, Chao and Kovacevic, 1990) and inserted accelerometers in bones (Hennig and Lafortune, 1991), *in vivo* kinetic measurements on humans are still clearly impractical to allow for complete analysis of the sources of power during a given motion (Lieber, 1990). Thus, in most cases, biomechanists proceed indirectly to estimate muscle forces. They first create a link-segment model of the body with appropriately determined inertial characteristics. The external force(s) applied to that body is(are) measured and, in combination with kinematic measurements, permit(s) the estimation of net forces and moments of force at each articulation of the model. This type of analysis is referred to as ***inverse dynamics.***

The model mentioned above, as complex as it may be, consists of a flexor and an extensor muscle or group of muscles on each side of every joint. Based on anatomical considerations it is expected that, as the words imply, a joint would be flexed by a flexor and extended by an extensor muscle. Biarticular muscles cross two joints and can, in this regard, have a distinct function at each joint. The rectus femoris muscle, for example, acts as a knee extensor and as a flexor of the hip. Several mechanisms have been proposed to explain the mechanics biarticular muscle activity. Some researchers have suggested that in some controlled motions, certain two-joint muscles could have an role that is opposite to their normal or anatomically expected action. Such a muscle function has been called ***paradoxical.***

Early in the 20th century, Lombard (1903) proposed that cocontraction of the antagonist biarticular muscles of the thigh can cause simultaneous extension of the knee and hip joints. This assertion is grounded in the fact that, on the side of the joints that is linked to extension, the muscle tendons are inserted further from the centre of rotation of each joint, thus providing a better leverage for extension. That situation has been known as ***Lombard's paradox***. Lombard later sought to validate his theory looking at the leg of the frog (Lombard and Abbott, 1907). The frog leg, nevertheless, differs from the human segment in that the tibialis anterior muscle is biarticular, dorsiflexing the ankle and extending the knee.

Along the same lines, Rasch and Burke (1978) described a potential for ***tendinous*** or ***belt-like*** action from the biarticular muscles that cross the knee and hip joints. The concept was not new, however, as it had clearly been put forward as early as 1867 by Cleland. As in a closed pulley system, energy would be transferred to the other side via the taut muscles. In this case hip extension would cause an extension of the knee and *vice-versa*. As remarked by these authors the hamstring group is, in most individuals, sufficiently tight to exert tendinous action at low levels of contraction. In this respect, knee flexors (the hamstrings muscles) may contribute indirectly to the extension of that joint although this does not constitute a paradox.

Molbech (1965) and Carlsoo and Molbech (1966) developed a geometrical model of the lower segment to discern the paradoxical behavior of biarticular muscles. These investigators reported paradoxical activity of the biarticular muscles of the thigh during deep knee bends using electromyographic (EMG) signals as a criterion. The cocontraction of the hamstrings with the quadriceps group is no surprise since one can, by palpation alone, detect the activity of the hamstring while sitting up from a chair. (This specific case of raising from a chair has been substantiated by EMG measurements from Kelley, Dainis and Wood (1976).) Muscle activity, however, does not exclusively imply that the contracted muscles contribute to cause the motion that is observed; there is also possibility of antagonistic and of stabilizing action.

Some biarticular muscles may well work in a paradoxical fashion. Albeit, more tools than solely electromyographic measurements are needed to detect the occurrence of paradoxical action assertively. As pointed out by Andrews (1987), the classification method used to determine the functional role of a biarticular muscle influences the detection of paradoxical behavior. Carrière and Beuter (1990) underlined the need for a combination of EMG, kinematics, and kinetics data to better understand biarticular muscle activity during leg extension. An estimation of the instantaneous change in muscle length and the prediction of joint forces, combined with EMG measurements, definitely constitutes a practical instrument to determine muscle function. In addition, researchers may gain in examining well constrained motions. Doing so would reduce the need for stabilization of the joint(s) by muscles that could potentially exhibit a paradoxical role.

Purpose of the study

This investigation was to provide a deeper understanding of the functional role of the lower extremity musculature during the drive phase of the rowing motion. The technique, which combines EMG measurements with muscle kinematics and joint kinetics, allows for the detection of potential differences in leg muscle recruitment between male and female athletes during ergometer rowing. The hypothesis that the biarticular muscles acting upon the knee function in a paradoxical fashion during knee extension was tested.

Delimitations

The scope of the study was kept within the following boundaries.

1. Only elite level athletes were used in this study because they perform the rowing motion efficiently; hence, each muscle contraction has a purpose.
2. The testing protocol ensures that no detrimental fatigue can affect the muscular recruitment pattern during the test.
3. The subjects are from the same region: athletes from the National Capital area.

Assumptions and limitations

1. The viscous frictions within the muscles and the frictions within all joints are negligible.
2. The change in the location of the centre of rotation of each joint relative to its rigid segments during the movement is negligible; each joint is considered as a pin-connected hinge.
3. Each subject has normal anatomical characteristics.
4. A four segment link mechanism representation of the musculo-skeletal system, in which each segment is considered as rigid, provides sufficient accuracy.
5. The electromyographical signal (EMG) reflects the active state of the muscle.
6. All active myofibrils within one muscle contract homogeneously.
7. The moment of force a muscle generates at its tendon is applied in one single direction.

8. During rowing, the motion of the lower body segments is symmetric and constrained within one plane which warrants the validity of a two-dimensional analysis.

Significance of the study

The results from this investigation may confirm the possibility that the biarticular knee flexor muscles act paradoxically during the extension of the knee. To date such a function has been proposed but never confirmed. Beyond the results relating to the paradoxical action of two-joint muscles, the development, refinement and testing of a specific instrument should facilitate or guide further research in the assessment of muscular function.

Knowledge of the role of biarticular muscles in rowing may lead to a deeper understanding of other activities. Crucial information could then be available for rehabilitation and therapy both within and outside the sport context.

A more precise knowledge of the contribution and recruitment pattern of the muscles used in the rowing motion should provide a basis for developing sound training strategies. The understanding of the lower segment's muscle function while rowing the Gjessing ergometer can possibly be extrapolated to sweep rowing. Detection of potential disparities or similitude in muscle recruitment between genders could constitute an important benefit to the sport. As pointed out by Nelson and Widule (1983), one of the issues that remains to be addressed pertains to similarities and differences in the biomechanical characteristics of male and female rowers. In addition, the technique, and therefore the performance of the activity, may be positively affected by a precise knowledge of the role of the main muscles of the leg. Pertinent training directives could be used by the coach to optimize the athlete's preparation for his/her event. The identification of anatomical weaknesses would have direct implications in the establishment of more specific dry-land and rowing programs. Above all, weight training could be more specifically focused on the athletes' needs.

Methods

Subjects

Five male and four female elite rowers from the National Capital region served as subjects for the study. Most of these athletes were or had been rowing at provincial or national level. Each subject had to be free of neurological and pathological problems and must not have had a history of surgery at any joint or muscle of the lower segment. Athletes from the local rowing community were contacted; the first nine that volunteered and who met the above criteria were used in the study. Prior to being involved in the study, the subjects were screened according to the modified PAR-Q questionnaire. Each subject also had to read and sign an informed consent form which had already been approved by the Human Research Ethics Committee of the University (see Appendix C).

Experimental protocol

The testing session included the preparation of the subjects (skin preparation placement of electrodes for electromyography (EMG), anthropometric measurements and positioning of self-adhesive reflective markers at the anatomical landmarks) and a minimum of five to ten minute warm-up on the machine, which duration was decided upon each subject's preference and comfort with the instrument. Most athletes had had previous exposure to the type of rowing ergometer to be used (Gjessing-ErgOrow) although, to familiarize everyone, each subject had to row the machine for four bouts of two minutes, interspersed by two minutes of rest. The workload (resistance of a friction belt rubbing on the flywheel) consisted of 25 N (2.6 kp) and 30 N (3.1 kp) for females and males, respectively. These workloads approximate those formerly used for the official testing protocol of the Canadian Amateur Rowing Association and were not to induce detrimental fatigue during the test.

The test involved the rowing of the Gjessing ergometer, consistently, for at least twelve entire cycles (from catch to catch) at a rate of 27 strokes per minute. All measurements, with the exception of the cinematographic recording of three strokes, took place over a period of 30 seconds to register ten consecutive strokes. Sampling began when the rower had reached the stroking rate according to the beat of an electronic metronome. Prior to and following the test, the rowers performed maximal pulling and pushing actions against fixed resistances to allow for the determination of the maximum EMG levels for amplitude normalization.

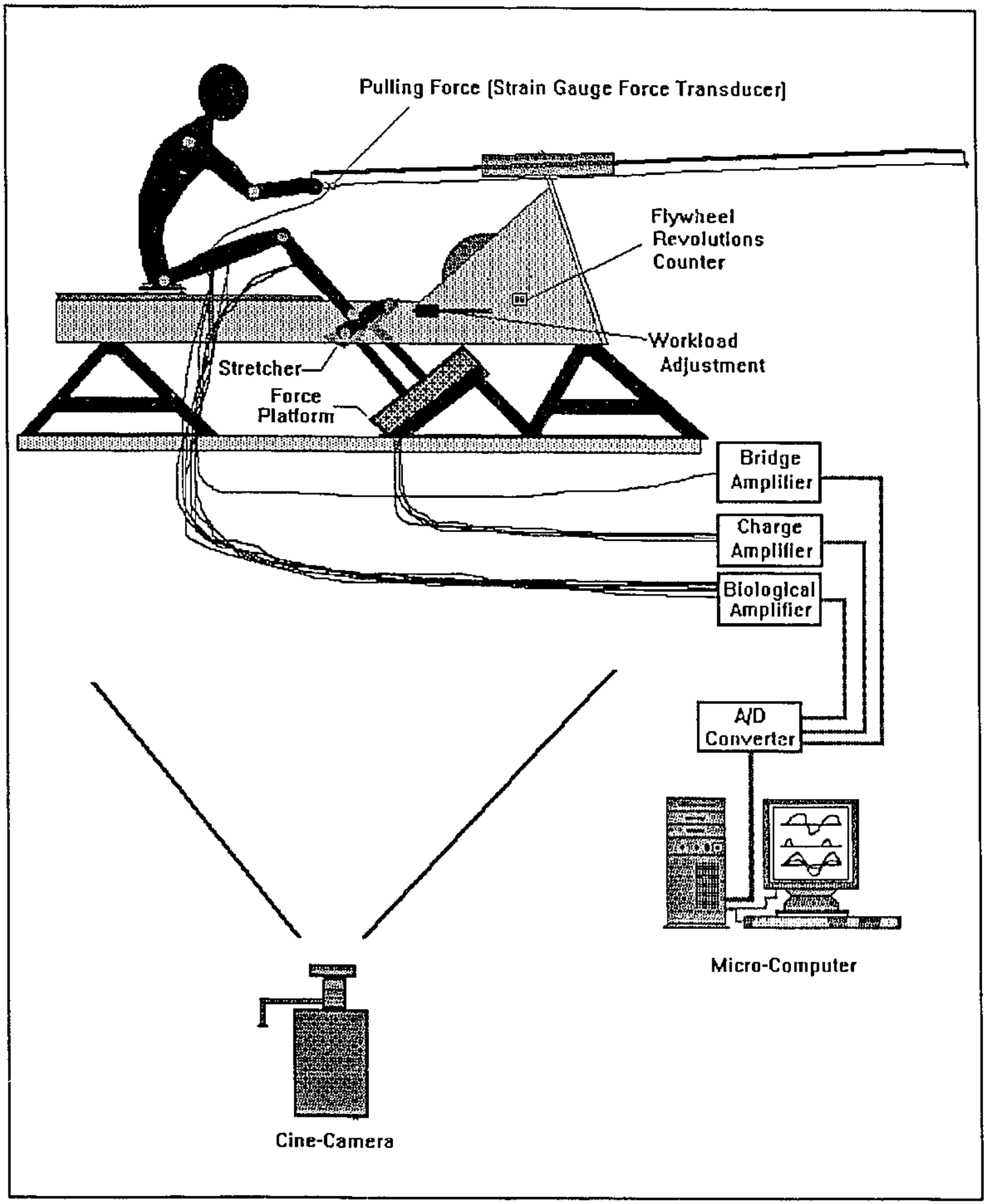

Figure 1. Experimental setup.

Data Acquisition

EMG

The EMG activity of the following muscles of the left leg was measured with surface electrodes (Medi-Trace: silver/silver chloride pellet electrodes): the biarticular biceps femoris, rectus femoris, gastrocnemius and the monoarticular soleus, gluteus maximus and vastus lateralis. These muscles have been selected as they are the prime movers of the leg and are suitable for surface EMG recording.

The skin was prepared to reduce the resistance between two adjacent electrodes to less than 20 kΩ. The self-adhesive electrodes, with their centres 2.5 cm apart, were placed on the skin at each motor point as described by Delagi, Perotto, Iazzetti and Morrison (1980). The sampling took place over ten consecutive cycles. Each signal was amplified (gain of 2000) and full-wave rectified by a differential bioamplifier with built-in second order band-pass filter (10-700 Hz). Low-pass analog filtering, with a cutoff frequency of 6 Hz, provided linear envelope EMG (Winter, 1990). This linear envelope was sampled through an analog-to-digital (A/D) converter at 200 hertz and stored by a microcomputer.

The linear envelope EMG was normalized to each subject's maximum EMG level and expressed as a percentage. The maximum EMG levels were obtained from maximum voluntary contractions (MVCs) in pulling and pushing against a fixed resistance while sitting in the rowing position. For pulling, two belts were attached to the front of the ergometer frame and to the oar handle, hindering the motion of the oar handle. Maximum pulling on the handle elicited maximum activity of the foot plantar flexors, the knee extensor and the hip extensor muscles. A band placed at hip level and held by an assistant impeded forward motion during an attempt by the subject to push the oar handle forward (to simulate recovery); this allowed maximum solicitation of the knee and hip flexors. The EMG signal was also time normalized to the duration of each cycle to provide a more accurate time base for comparison between subjects.

Direct Force

The forces applied by the rower's feet were measured directly with a force platform (Kistler). For this purpose, the Gjessing ergometer had been mounted on a frame that has been especially designed to allow for the insertion of the force platform underneath it. The platform was installed on an incline isolated from the ergometer and it supported the foot stretcher (see Figure 2). The force plate instrumentation also provided the position of the centre of pressure relative to the centre of the platform.

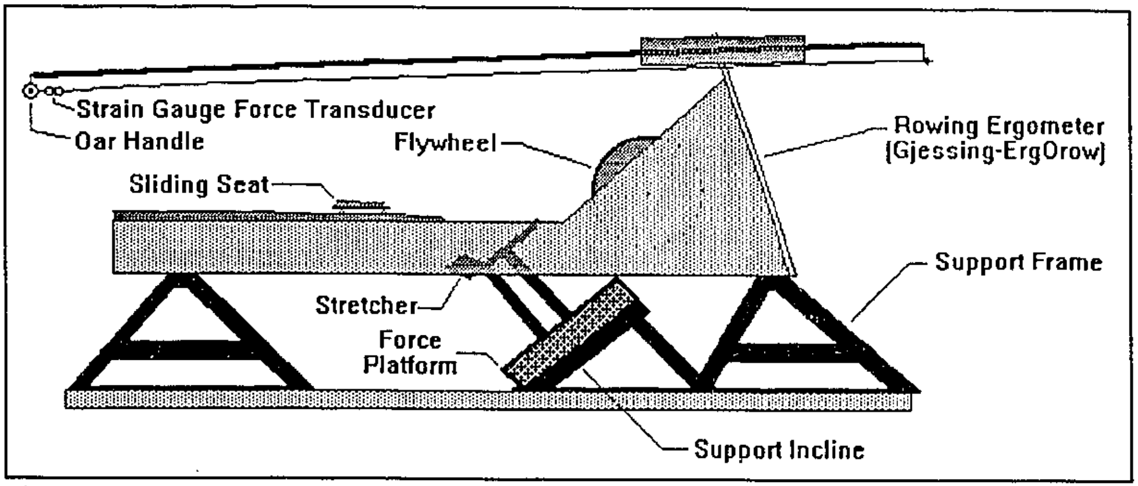

Figure 2. Side view of the apparatus.

In addition, the force applied to the handle (simulating the oar) was sampled through a strain-gauged force transducer linking the pull cable of the ergometer and the handle. The signal was conditioned by a bridge amplifier and the amplitude of the output voltage from the amplifier was stored for future reference.

All the force signals were sampled and A/D converted at a frequency of 200 hertz. This is well over the requirements of the Sampling Theorem (Cobbold, 1974) since the cycle's period is less than 2 seconds (at approximately 27 strokes/minute). The force and EMG data were simultaneously collected by the same A/D converter and stored by the same microcomputer. For subsequent comparison, all the force data was normalized over time—and expressed as a percentage of the drive—to compensate for differences in stroking rates among subjects.

Cinematography

A motion picture camera (Locam) was used to record three complete rowing cycles on 16 mm cinefilm. Prior to filming the subjects, a 5 X 9 grid board with pre-positioned coordinates was filmed in the plane of the motion to provide a standard and to allow for later corrections of linear distortions caused by non-orthogonal view during filming and projection. A side view of the whole rowing motion (perpendicular to the sagittal plane) enabled position recording of the following anatomical landmarks to be later digitized: toes (fifth metatarsal-phalangeal joint), ankle (lateral malleolus), heel, knee (lateral femoral condyle), hip (greater trochanter), shoulder (acromion process), head (ear), elbow (radiale). These represent the locations of the centres of rotation of the joints and the extremities of the link-segment model (Dempster, 1955).

The sampling rate of the camera (shutter speed) of 50 frames/second was synchronized with the force and the EMG signals by a hammer blow visible in the plane of motion and applied directly to the force platform during the sampling. The force spike induced by that synchronization blow was later filtered if it occurred during the drive phase of the stroke.

For one drive (extension) phase and its previous and subsequent recovery, each projected image of the cinefilm—approximately 7 % of life size—was digitized with a digitizer (HP 9874) to provide two-dimensional (*x*,*y*) coordinates for each of the eight anatomical markers, the oar handle and one static reference point. Kinematic information was derived from the displacement of these coordinates from frame to frame.

Biomechanical Model

For the purpose of this study, the human body was modeled as a four-link rigid body system: trunk, thighs, shanks and feet (see Figure 3). All joints were assumed to be frictionless hinges. The inertial characteristics of the segments were calculated from each subject's anthropometric measurements and from the tabulated data of Dempster (1955) as modified by Plagenhoef (1971). Inertial characteristics refer to segmental mass, radius of gyration, moment of inertia and position of the centre of gravity.

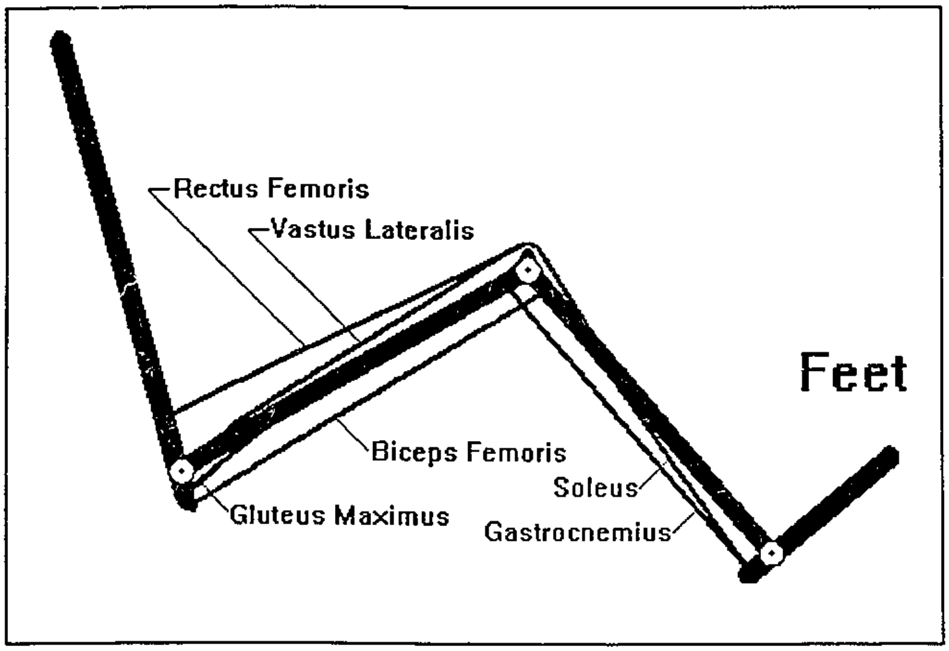

Figure 3. Link segment model representing the rower.

Since the tension in a muscle varies with its length and its velocity of contraction (Winter, 1990), the span of each muscle under investigation was determined; joint angles were measured (see Figure 4) and the instantaneous length of the muscle and its tendon (muscle-tendon unit) were estimated with the use of Frigo and Pedotti's linear equations (1978) as modified by Hubley (1981). These equations are described in detail in Appendix A. From the muscle-tendon length, the muscle contraction velocity (approximate rates of shortening or lengthening) were derived for each of the six muscles under investigation. The instantaneous angular velocities of the hip, knee and ankle joints were also determined.

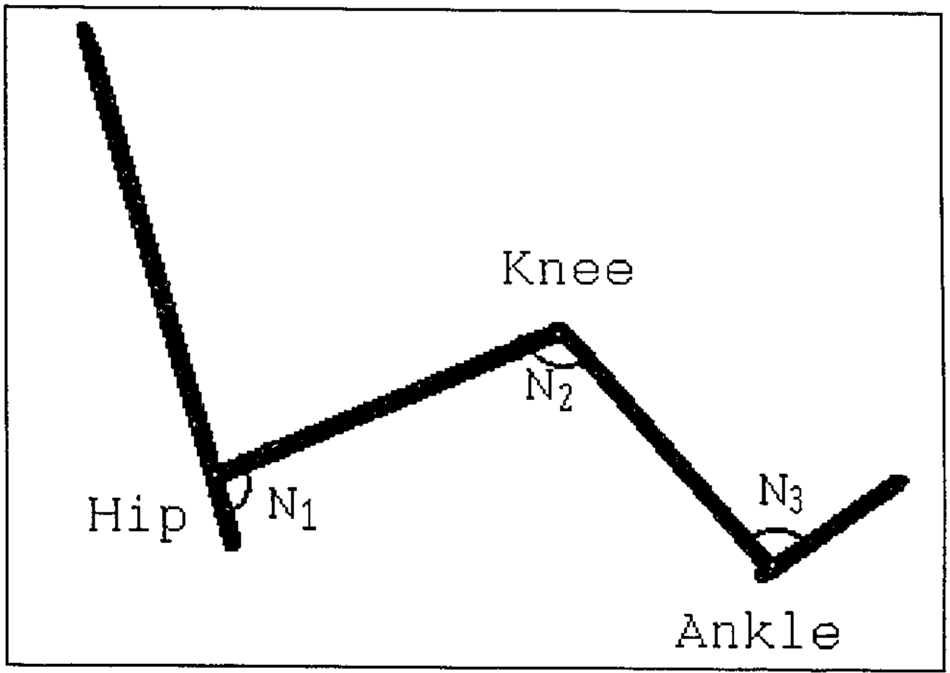

Figure 4. Muscle-Tendon Unit model reference.

Data Processing

To quantify better the EMG activity, each muscle's linear envelope EMG history was averaged over ten consecutive cycles to produce a single curve representing the mean of the ten filtered signals. The kinematic information drawn from the digitization of the cinefilm was filtered to eliminate noise and movement artifacts (fourth order, critically damped low-pass Butterworth digital filter with cutoff frequency of 6 Hz). Inverse dynamics (Winter, 1990) was then applied to compute the net joint moments of force and the joint reaction (internal) forces at the hip, knee and ankle joints. Finally, for each subject, the instantaneous powers produced by each moment of force was computed from the product of the net moment of force times the joint angular velocity.

Classification Scheme for Muscle Function and Determination of Anatomical Paradox

A truth table was produced for every muscle to determine its function. To assess whether biarticular knee muscles behave paradoxically during knee extension, the following conditions must hold. First, the net moment of force crossing the knee joint must be extensor and produce positive work (*i.e.*, positive power). Second, the biarticular muscles must be in a state of contraction. The basic criterion for the determination of significant muscle activity was chosen as 25% or more of the maximum EMG level (which was based on one MVC). Accordingly, an EMG level lesser than 25% of the maximum was considered too low for the muscle to contribute significantly to the movement. Third, the muscle must be contracting concentrically, that is, it must be shortening. An isometric or eccentric contraction of the muscle would imply a stabilizing function. Needless to say, this algorithm can serve to define the function of the monoarticular muscles examined as well. Finally, the role of each active muscle was determined by the direction of the moment it creates; if the direction of that moment is similar to that of the net moment at the joint, the muscle is depicted as being an agonist. If the muscle moment and the net joint moment directions are opposite, the active muscle is seen as an antagonist (Andrews and Hay, 1983). The following table (Table 1) shows the eighteen possibilities; looking exclusively at the extension phase of the rowing motion limits the possibilities to cases number seven to twelve. For cases five and eleven, biarticular muscles could also be acting at their other joint. The possibility of waste through inefficient antagonist muscle contractions is rejected based on the premise that, in skilled athletes, each muscle contraction has a purpose. Any stabilizing or acting at the other joint is described, however, as antagonistic activity.

Table 1. Truth table depicting muscle function at one joint.

Case	Direction of Joint Movement	Muscle's Theoretical Function	Net Joint Moment Direction	Type of Contraction	Muscle Function
1	flexion	flexor	flexor	concentric	agonist
2	flexion	extensor	flexor	concentric	[a]**paradoxical** agonist
3	flexion	flexor	extensor	concentric	stabilizer or antagonist[b]
4	flexion	extensor	extensor	eccentric	agonist (speed control)
5	flexion	flexor	none	concentric	stabilizer or cocontraction[b]
6	flexion	extensor	none	eccentric	stabilizer or cocontraction[b]
7	**extension**	**extensor**	**extensor**	**concentric**	agonist
8	**extension**	**flexor**	**extensor**	**concentric**	[a]**paradoxical** agonist
9	**extension**	**extensor**	**flexor**	**concentric**	stabilizer or antagonist[b]
10	**extension**	**flexor**	**flexor**	**eccentric**	agonist (speed control)
11	**extension**	**extensor**	**none**	**concentric**	stabilizer or cocontraction[b]
12	**extension**	**flexor**	**none**	**eccentric**	stabilizer or cocontraction[b]
13	------	flexor	flexor	isometric	agonist
14	------	extensor	flexor	isometric	antagonist - stabilizer
15	------	flexor	extensor	isometric	antagonist - stabilizer
16	------	extensor	extensor	isometric	agonist
17	------	flexor	none	isometric	stabilizer or cocontraction[b]
18	------	extensor	none	isometric	stabilizer or cocontraction[b]

Note. A muscle is considered active when its EMG level is at least 25% of the pre-recorded maximum.

[a] Biarticular muscle only.

[b] Waste.

Results

On all graphs the first two letters of the trial code, *rf* or *rm*, stand for rowing female or rowing male, respectively. Figure 5 shows a stick figure of the kinematic pattern as digitized from the cinefilm and includes the stretcher reaction force for the drive phase of one rowing stroke from a male athlete. Figure 21 (Appendix D) portrays the same parameters for the entire stroke (*i.e.*, including the recovery). A sample screen of the force and EMG patterns as provided by the force platform software Bioware (version 2.0) is displayed in Figure 6. All the curves on that figure are plotted against the same time base. For clarity, all the signals presented in Figure 6 have been filtered successively with a moving average and a moving median over a five data point range. Although the forces along the three axes were recorded and used in the analysis, only the sagittal (*y*) and the frontal (*z*) forces are represented on the top graph of Figure 6 (lateral forces being random and of negligible amplitude would have hindered the view). The bottom section of that figure presents a sample of the ergometer handle (oar) force signal as provided by the strain-gauge force transducer. On the same graph is plotted the linear envelope of the EMG signal for one of the six muscles investigated: biceps femoris.

To avoid the loss of information that would have been caused by averaging between subjects, the results were looked at individually. The reader should be aware that, for the purpose of this study, the drive phase was defined as when pressure is applied to the stretcher. Thus, a negative force (a backward pull on the stretcher) would be considered as part of the recovery. This systematic phase determination method

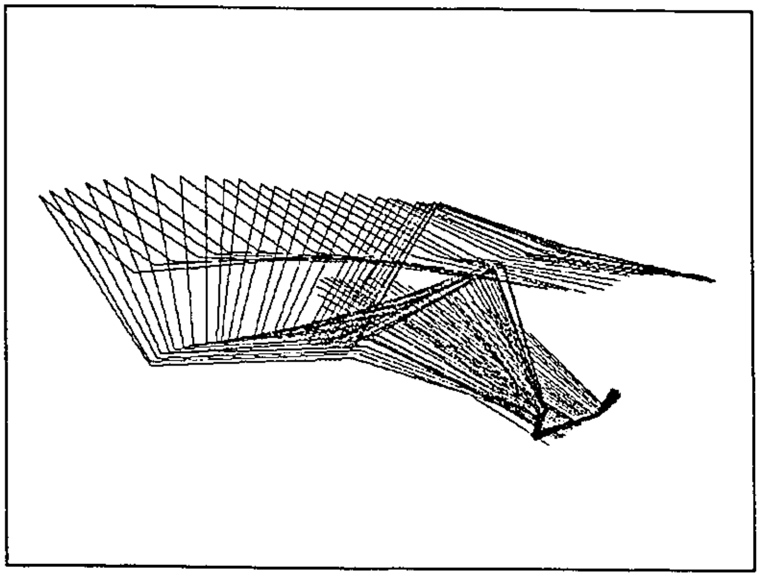

Figure 5. Stick figure of the kinematic pattern and stretcher reaction force for the drive — male ergometer rowing — *rmbs*.

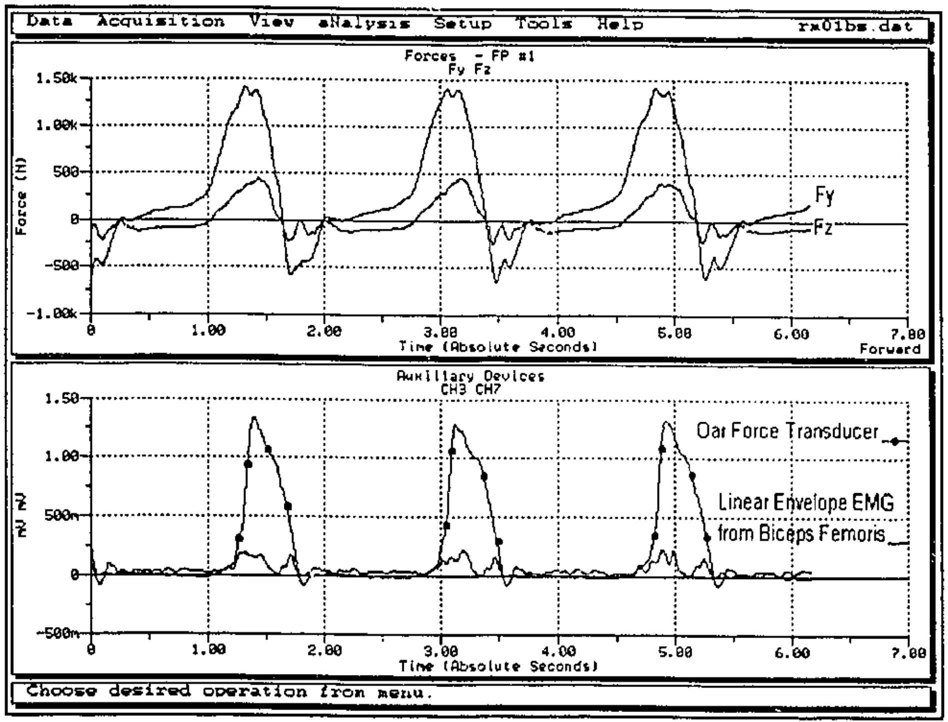

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Figure 6. Force patterns and EMG signal from one muscle.

will lead to a somewhat different temporal division of the cycle when compared to rowing on the water where the entry of the oar in the water (catch) and its exit are the criteria. It is, however, more inclusive in that it entails a longer drive period than would a measure of the force on the oar handle and it is warranted by the exploratory nature of the present study. For instance, here, the knee can be flexing while an extensor moment is necessary to stop the forward momentum at the end of the recovery (beginning of force application to the stretcher).

A series of representative curves summarizing the results of the joints kinematics and kinetics analysis for one subject is presented in Figures 7 to 9. The results from the other subjects are included in Appendix B (Figures 22 to 45). To facilitate comparison between subjects, the powers at each joint for all the subjects have been grouped by gender in Figures 10 and 11. When looking at the magnitude of the net joint moment of force and the joint power curves, it should be kept in mind that work was done by both legs. To enhance the description of the results from the inverse dynamics analysis, the angular joint velocity, the net moment of force and the power curves at each joint have been divided in three phases. The choice for this threefold division rests on the trimodal trend exhibited by the muscle contraction velocity curves (Figure 13 and 54 to 61 in Appendix B). Each phase roughly represents one third of the drive phase of the rowing cycle.

From Figures 22 to 33 it can be seen that the direction of the joints' angular velocity and the direction of the joints powers change in phase—from flexion to extension—for all the female subjects. The males' hip joint (Figure 7,8,9 and 34 to 45), however, extends at least 7% later during the drive than the knee and ankle (both of which start to extend at the same time). It should be pointed out that, because of the method used to determine the time of occurrence of the drive phase (onset of pressure applied to the force platform), the knee joint was flexing during the first third of the drive. During that same period, the hip is flexing and the ankle is dorsiflexing. The focus of the present study, however, was on the extension of the knee joint although it is germane to know how much work was done to decelerate the body and start the drive at the end of the recovery, particularly because a substantial impulse was produced before the knee actually started to extend.

For the six muscles under investigation, the linear envelope of each electromyographic signal has been averaged over ten rowing cycles and low-pass filtered at a cutoff frequency of six hertz. After amplitude normalization, the EMG curves (Figure 12 and 46 to 53) were plotted for the whole rowing cycle (drive and recovery) for every subject. On these curves, the drive was identified by ***catch*** and ***finish*** labels. To facilitate interpretation, the drive was divided into three equal phases and separated by marks on the horizontal axis. To help in the visual identification of muscle activity, the predetermined EMG threshold has also been delineated by a horizontal line at 25% of the maximum amplitude recorded. The maximum corresponds to the highest value from both pre-test and post-test normalization measurements. For one subject (***rmbs***), the flag identifiers for the drive did not appear valid: The EMG signal is read after the force has been applied to the stretcher. The EMG and muscle kinematics data from this subject are therefore not presented.

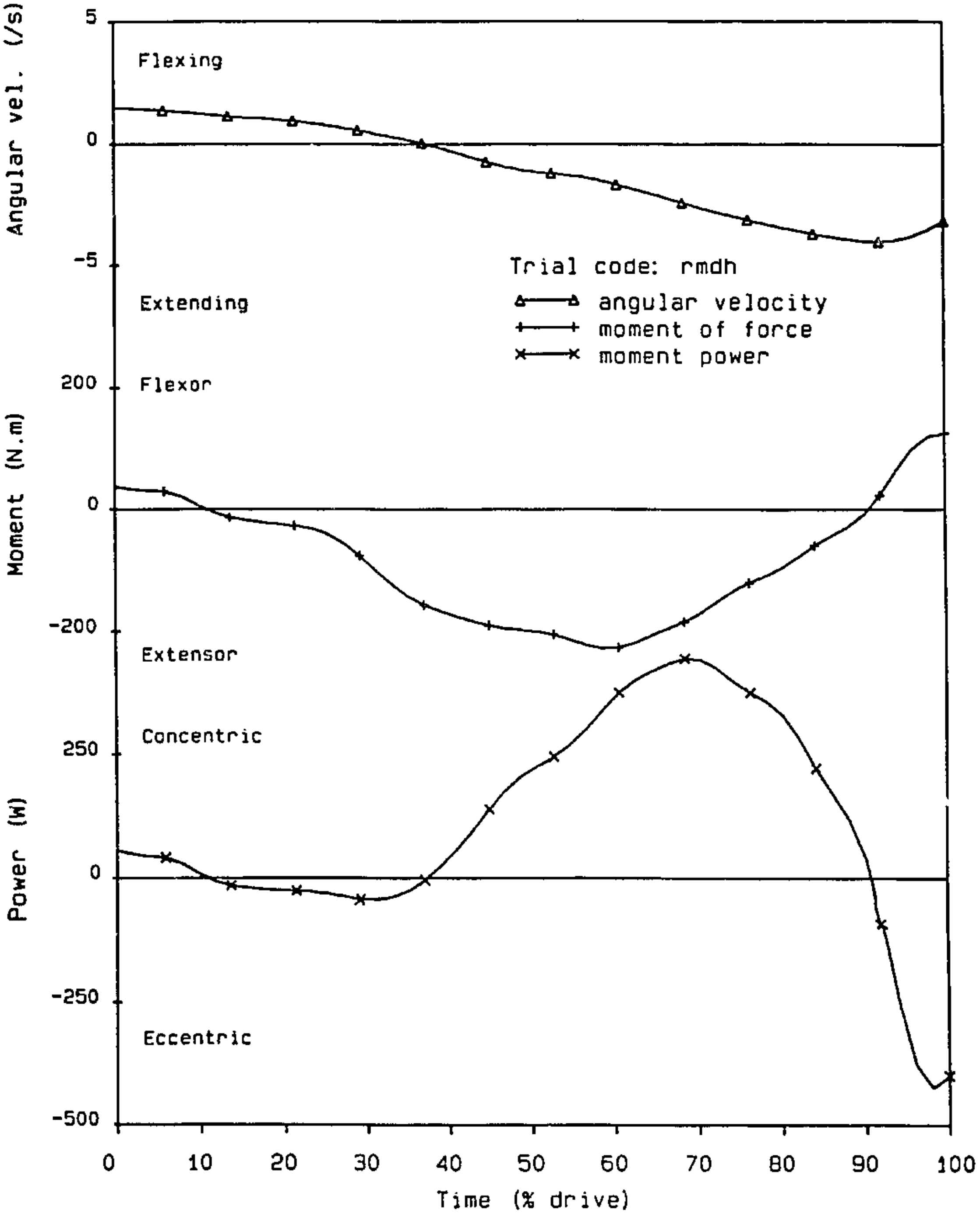

Figure 7. Hip angular velocity, net joint moment of force and power — male rower.

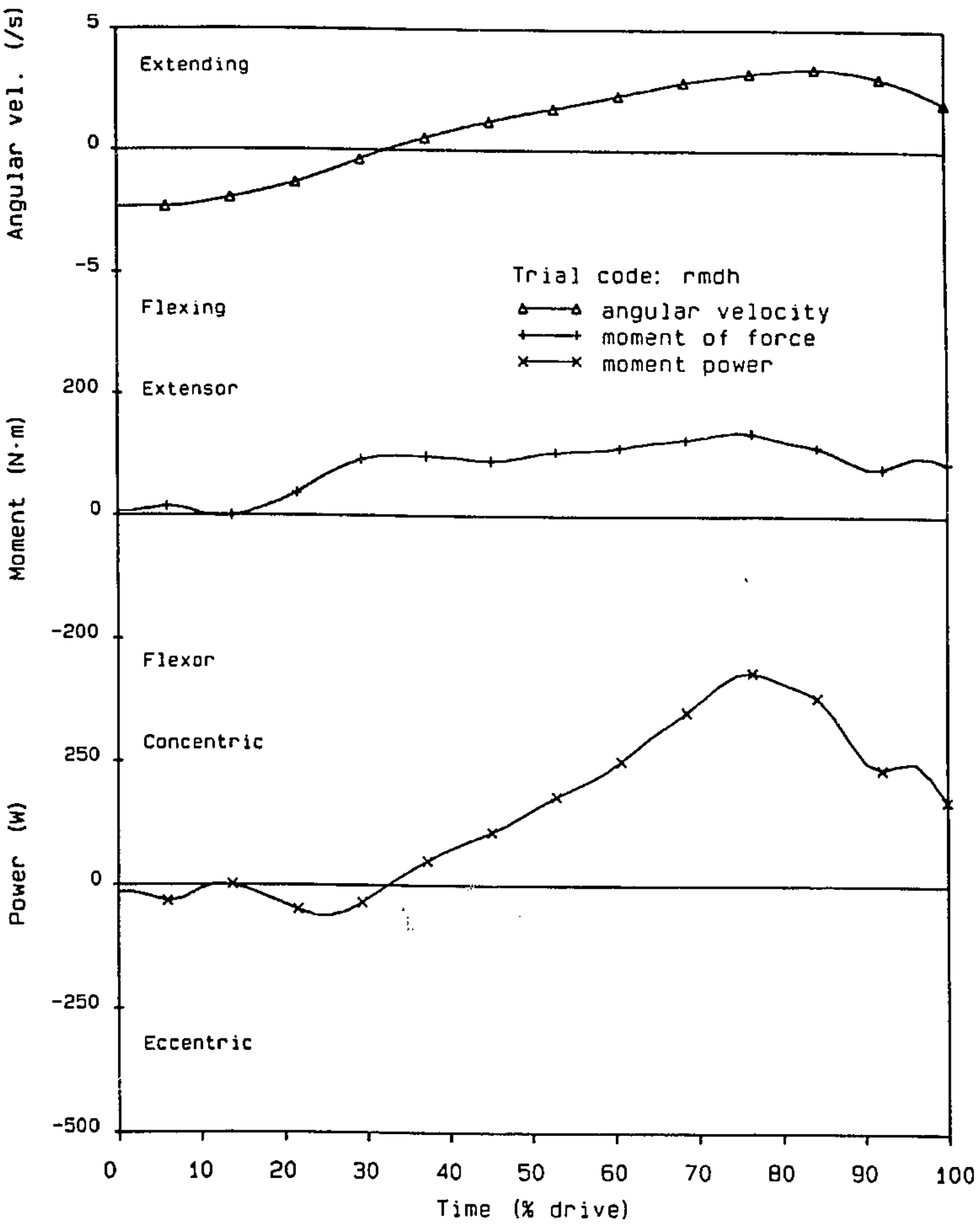

Figure 8. Knee angular velocity, net joint moment of force and power — male rower.

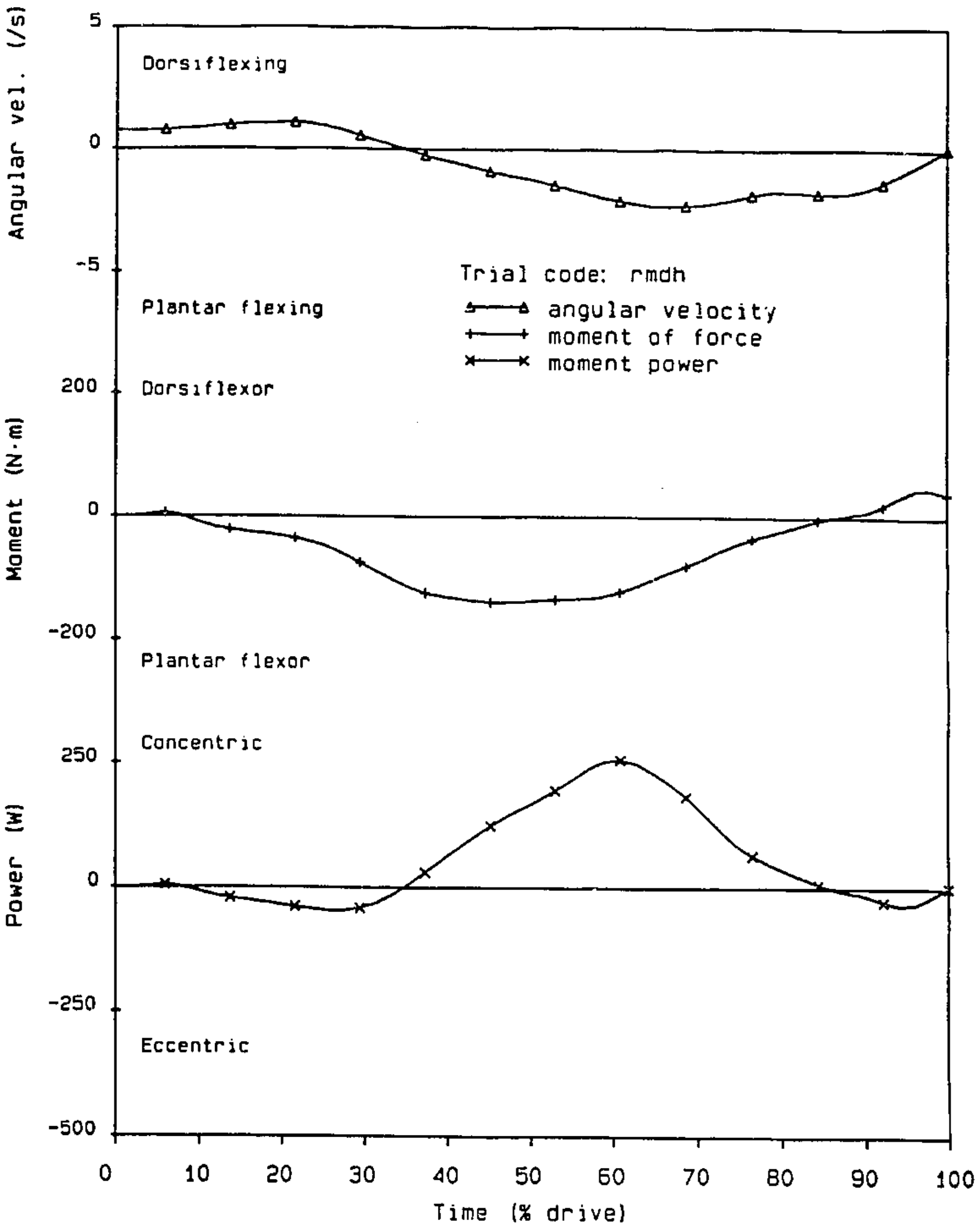

Figure 9. Ankle angular velocity, net joint moment of force and power — male rower.

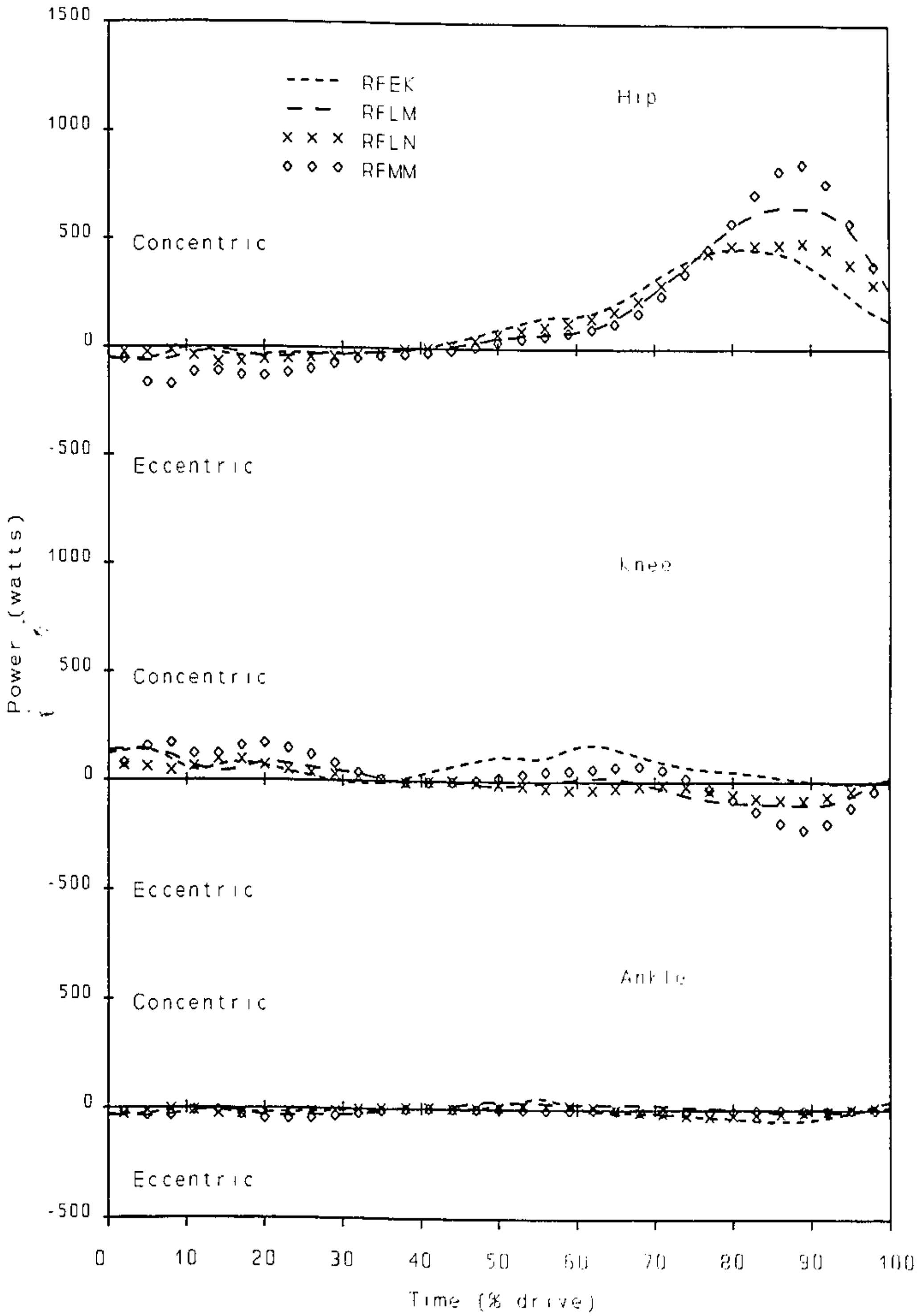

Figure 10 Powers at the hip, knee and ankle joints for the female subjects.

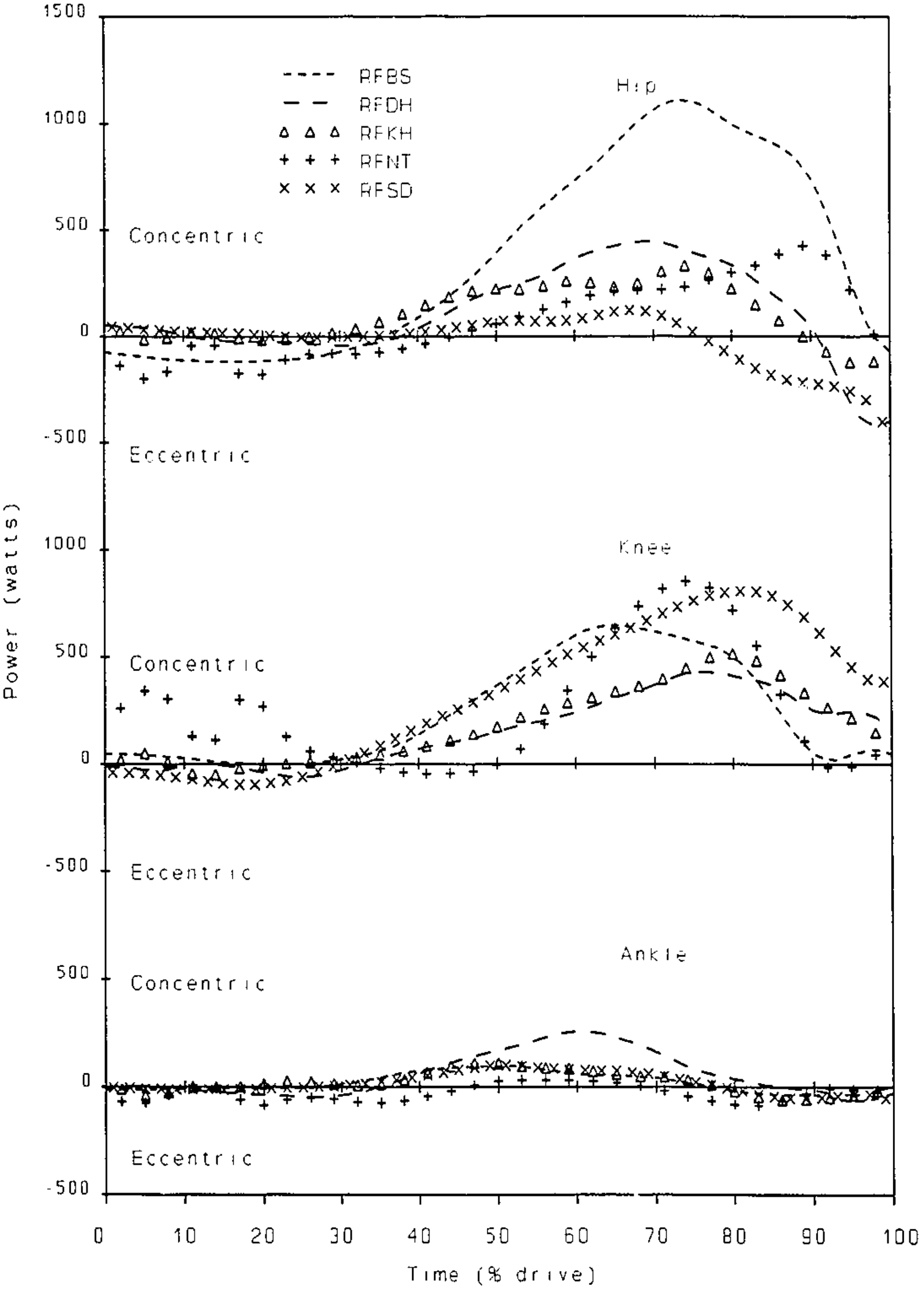

Figure 11 Powers at the hip, knee and ankle joints for the male subjects.

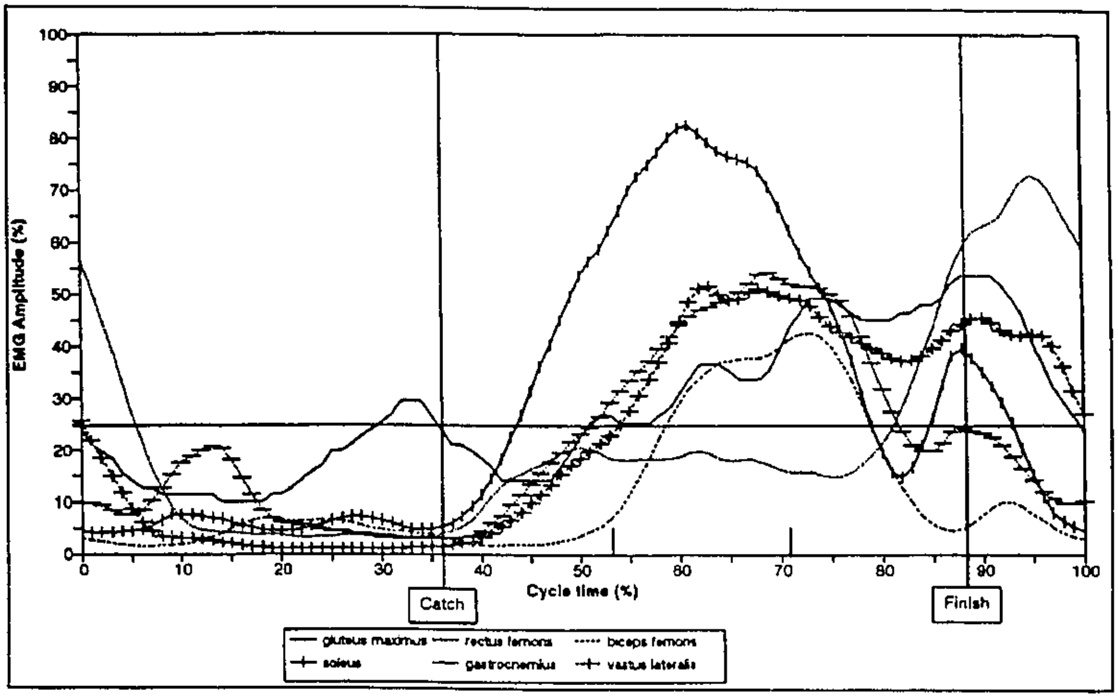

Figure 12. .Linear envelope EMG averaged over ten cycles for the six muscles — *rmdh.*

The muscle kinematics curves (Figure 13 and 54 to 61) represent the instantaneous rates of shortening or lengthening during the drive. As a curve crosses the horizontal axis, the muscle is in instantaneous isometric contraction. The contraction velocity of the six muscles examined changes direction three times in most subjects: The lengths of these muscles goes in phase from shortening to lengthening or *vice-versa.*

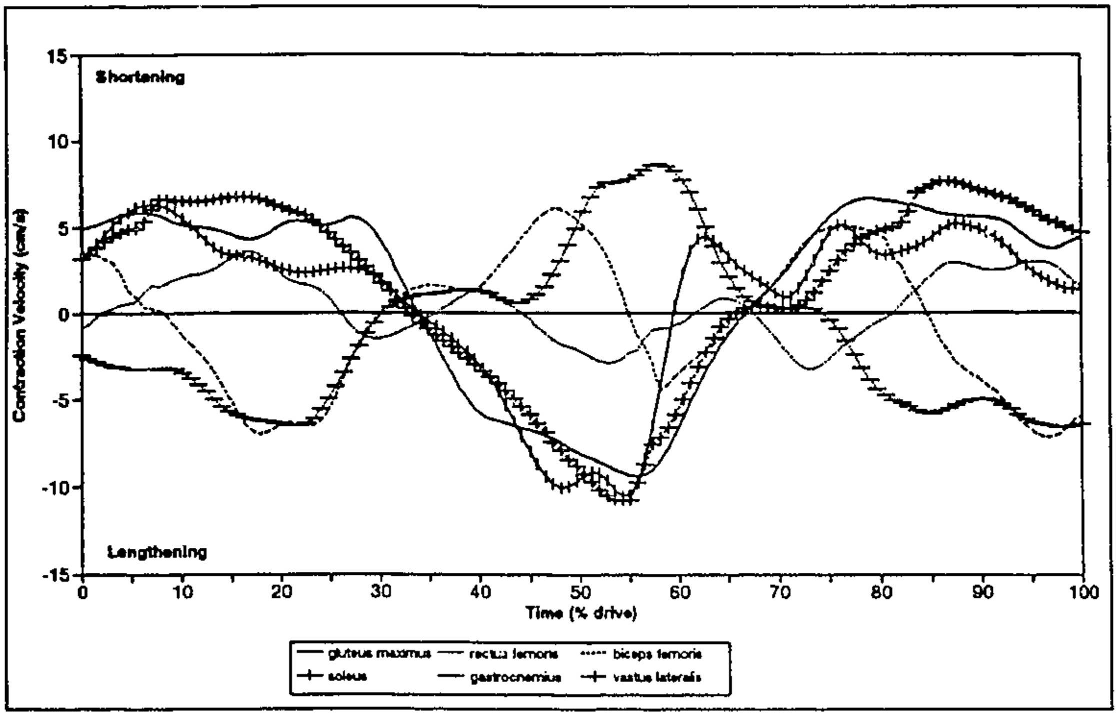

Figure 13. Muscle kinematics: contraction velocity for the six muscles — *rmdh*.

The reader should be reminded that two of the criteria chosen for the systematic determination of muscle function were: (1) the EMG level of the muscle has to be above 25% of the maximum recorded during the normalization trials and (2) the muscle must be contracting concentrically (positive contraction velocity). Conjoint fulfilment of these criteria is reported for each third of the drive in Table 2 which shows the number of subjects for whom each muscle displayed this behavior.

Table 2. Frequency of simultaneous occurrence of muscle activity and muscle shortening during the drive phase out of, respectively, four female (F) and four male (M) subjects.

	Drive (%)		
	0 — 33	33 — 66	66 — 100
	F M	F M	F M
gluteus maximus	1 — 1	0 — 1	2 — 3
rectus femoris	3 — 1	0 — 0	3 — 3
biceps femoris	0 — 0	3 — 3	0 — 2
soleus	2 — 4	0 — 0	1 — 4
gastrocnemius	4 — 0	4 — 3	0 — 0
vastus lateralis	2 — 1	0 — 0	2 — 3

Note. Muscle activity is implied when the EMG level collected from this muscle is equal to or greater than 25% of the pre-recorded maximum.

In Table 3, the occurrence of significant EMG activity in each muscle is presented in relation to the activity of the other leg muscles investigated. For instance, two out of four males displayed co-contraction of m. rectus femoris and m. biceps femoris during the last third of the drive. This information is of interest since the hypothesis of Lombard's paradox necessitates simultaneous action from antagonist biarticular muscles.

Table 3. Frequency of co-contraction occurrence as depicted by the EMG activity during the three thirds of the drive for the six muscles.

	GM	RF	BF	SO	GA	VL
			Males (n=4)			
GM	---	1-0-3	1-3-2	1-4-3	1-3-3	0-4-3
RF		---	1-0-2	1-0-4	1-0-4	1-0-3
BF			---	1-3-2	1-3-2	0-3-2
SO				---	3-3-4	1-4-3
GA					---	1-3-3
VL						---
			Females (n=4)			
GM	---	1-3-1	0-3-0	1-4-1	1-4-1	0-4-1
RF		---	0-2-0	2-3-1	2-3-2	2-3-2
BF			---	0-3-0	0-3-0	0-3-0
SO				---	2-4-0	1-4-1
GA					---	0-4-1
VL						---

Note. Abbreviations- GM: gluteus maximus; RF: rectus femoris; BF: biceps femoris; SO: soleus; GA: gastrocnemius; VL: vastus lateralis.

The following table (4) summarizes the frequency of occurrence of significant muscle activity, muscle shortening and concentric moment power. To assess the possibility of energy transfer via other muscles, the activity of each muscle is looked at, whether this muscle crosses that joint or not.

Table 4. Frequency of simultaneous occurrence of muscle activity*, muscle shortening and concentric joint moment power out of respectively four female and four male subjects.

		Drive (%)	
	0 — 33	33 — 66	66 — 100
	F M	F M	F M
		Hip	
	flexion	extension	extension
gluteus maximus	0 — 0	0 — 0	2 — 2
rectus femoris	0 — 0	0 — 0	3 — 3
biceps femoris	0 — 0	2 — 2	0 — 1
soleus	0 — 0	0 — 0	1 — 3
gastrocnemius	0 — 0	2 — 2	0 — 0
vastus lateralis	0 — 0	0 — 0	2 — 2
		Knee	
	flexion	extension	extension
gluteus maximus	1 — 1	0 — 1	0 — 3
rectus femoris	3 — 1	0 — 0	1 — 3
biceps femoris	0 — 0	1 — 2	0 — 2
soleus	2 — 1	0 — 0	0 — 4
gastrocnemius	0 — 0	1 — 2	0 — 0
vastus lateralis	2 — 0	0 — 0	0 — 3
		Ankle	
	dorsiflexion	plantar flexion	plantar flexion
gluteus maximus	0 — 0	0 — 0	0 — 0
rectus femoris	0 — 0	0 — 0	0 — 0
biceps femoris	0 — 0	0 — 1	0 — 0
soleus	0 — 0	0 — 0	0 — 0
gastrocnemius	0 — 0	0 — 1	0 — 0
vastus lateralis	0 — 0	0 — 0	0 — 0

Note. The bold print is used when the muscle crosses that particular joint and the shaded numbers indicate paradoxical muscle behavior.

*EMG ≥ 25% maximum.

Discussion

Force pattern

As shown in Figure 6 (top curve), the pattern of force is very consistent between strokes. In looking more specifically at one cycle, a dip in the "y" (sagittal plane) curve is noticeable at the middle of the positive phase. This depression was caused by the forward reach that took place at the end of the recovery; the rower reached out to maximize the distance for the entry of the blade in the water. Aside from increasing the range covered by the oar blade, the forward reach could provide a prestretch of the back and leg muscles to prepare for the drive. The push on the oar handle releases some of the force applied to the stretcher. From the onset of pressure (positive force) applied to the force plate to this depression, eccentric work was done to absorb the forward momentum accumulated during the active recovery. The end of the depression zone on the curve corresponds to the catch as force was applied to the resistance (flywheel). This is confirmed because the time when force was applied to the oar handle (bottom curve—Oar Force Transducer) coincides with the end of the depression.

Angular velocity, moment of force and moment power

Hip joint

As depicted in Figures 7-8-9 (and 22 to 45—Appendix B), at first the hip joint was flexing and the moment power was small to resist joint flexion in all subjects; this joint power was being developed to slow down the forward motion of the body previously incurred by the recovery. Since virtually no net moment is acting at the joint during that period, pre-stretch of the muscles for the extension that is to follow appears insignificant.

At the mid-period of the drive phase, the angular velocity curve exhibited a change in direction when the hip joint extends. In all subjects, as the hip joint extended, the net moment at the joint became extensor with an increasing magnitude. The joint power curves denote that important concentric work is being done at the hip in all athletes, with the exception of one male subject for which the burst of concentric power is minimal.

The end of the drive depicts continuation of hip extension with the expected tapering off towards flexion that is to come in the following recovery. The extensor moments were also decreasing in amplitude (see Figures 10 and 11). The joint power curves show that concentric work was still being done, although at a lesser rate.

It is noticeable that the burst of concentric work done at the hip by the female rowers occurred later during the drive than it did for the males. With regard to the magnitude of the powers as shown in Figures 10 and 12, the portions that can be attributed to the knee and to the hip can not be generalized for all males—this is not applicable to the female rowers since the power developed to drive the body backwards appeared to originate almost exclusively from the hip extensors. (It should be noted that what is called backwards here would be referred to as forward while rowing on the water.)

Knee joint

For all subjects, the first portion of the knee angular velocity curve confirms that the knee was flexing; this condition was outside the scope of this study but one can still notice that the amount of power developed to absorb the forward momentum accumulated by the body and the oar during the recovery is meagre. The soft tissues probably absorb this energy in a passive way (through a bumper effect).

The second third of the drive was, as expected, characterized by the extension of the knee joint. There was, however, a striking difference between males and females rowers. Virtually no work was done at the knee joint by the female athletes, whereas, in the males there was a substantial amount of power produced by the net moment of force. (The power from the moment of force was considered significant only in one female subject, ***rfek***, although of low magnitude.) For the males, the net moment of force at the knee was extensor which confirms the use of the extensors at that joint in the thrust of the drive.

The third phase of the drive was still characterized by the absence of work done at the knee joint in all the female subjects. The curves for the male rowers displayed considerable net extensor moment and moment power that tapered off by the end of that period.

Ankle joint

For the first third of the drive, the angular velocity curves (Figures 7 to 9 and 22 to 45) show dorsiflexion in all subjects; the forward motion of the body was then decelerated and a modest eccentric power confirmed that energy was absorbed by the plantar flexors. This corresponded to the slowing down effect necessary to absorb the momentum accumulated during the active recovery. A light flexor moment was also seen which suggested pre-stretch of the plantar flexors for the ensuing phase.

The second third showed plantar flexion depicting the contribution of the plantar flexors to seemingly propel the rower backwards. In the males it was characterized by a small burst of concentric power to drive the body backwards.

During the last third of the drive, the angular velocity curve showed that plantar flexion was ending: the recovery was to start.

For the whole drive, the magnitude of the net joint moment and moment power was nevertheless generally low; practically no work was done at the ankle joint for the female rowers examined. This was also true in the males since the maximum power at the ankle was around six orders of magnitude less than the maximum estimated at the hip. (The results from subject *rmdh*—Figures 7-8-9—are an exception to this trend.)

Common discussion

There was an important difference in the way the female rowers tested performed on the ergometer when compared with the males. The fact that these women drove the oar and their body with the almost exclusive use of their hip extensor muscles, without producing power at the knee as the males did, is of interest. Differences in anatomical structures may account for the discrepancy. Skeletal configuration, muscle mass distribution, positional attachment of tendons (mechanical advantage) and general flexibility are all factors which can influence the way every muscle is recruited. It is also possible that a deficiency in strength at the knee extensor level caused the lack of power observed at the knee in the female subjects. Perhaps more important was the way local females were taught to row.

It is also interesting that, in each of the female rowers examined, the three joints extended simultaneously, whereas, for the males the hip joint commenced extension approximately 7% later than the coinciding ankle and knee extensions. The male rowers might have been taught to push their trunk backwards later during the drive, sequencing the work done by the major muscle groups and/or might be anatomically favoured to do so. All-in-all, the testing of a larger sample of subjects would bring more credibility to the fact that the sex differences observed were gender related rather than random.

The values of net joint moment and moment powers represent the work done by both sides of the body. This partly accounts for the generally low magnitude of the net moments and the powers in ergometer rowing when compared with other activities such as running. Moreover, the fact that the magnitudes of the net joint moments and powers at all joints in all athletes never exceeded 250 N•m and 1100 W, respectively, reflects the endurance nature of the activity. (These maximum values were found for the hip joint.) For instance, maximum values of net joint moments in running have been reported by Robertson and Taunton (1982) to be in the order of 350 N•m at the knee and 400 N•m at the ankle. Elftman (1940) presented values of joint power for running: approximately 3000 W at the hip, 1000 W at the knee and 3000 W at the ankle. Robertson and Lemaire (1988) estimated moment powers of 2696 W at the hip and -2342 W (eccentric extensor) at the knee during sprint running in males. For women, the same authors found 1731 W and -1083 W, respectively.

EMG and muscle contraction velocity

Table 2 summarizes how often a significant EMG level coincides with the shortening of the muscle; in most instances, the number of female subjects exhibiting these occurrences is close to the number of males. Table 3 is a summary of the muscular co-activations occurring during the drive. From this table, the biarticular antagonists rectus femoris and biceps femoris contract simultaneously while the knee joint extended in two male and in two female subjects. This makes Lombard's paradox plausible as a way to extend the knee joint in humans.

The possibility of energy transfer through taut biarticular leg muscles (from passive tightness or from muscle activity) can also be examined through Table 3; because of the classification method used, transfer through naturally taut biarticular muscles cannot be ascertained. The probability that the monoarticular muscles would do the work at one joint while and their biarticular counterpart would transfer energy to the next joint can be assessed; if concentric work was done at the hip by the monoarticular gluteus maximus as the knee was extending with concentric power, energy could be transferred to the knee via m. rectus femoris. This was the case for three male subjects during the last third of the drive. For two of these three instances, m. rectus femoris was shortening and, therefore, could have been producing by itself the power at the knee. This was determined by the results from the joint kinetic analysis. By the same token, belt-like energy transfer—energy produced at another joint—cannot be ruled out as a possibility to provide energy to the knee. The same rationale can be applied to the transfer of power generated by the plantar dorsiflexors to the knee via the biarticular gastrocnemius.

Unfortunately, the activity of the main plantar dorsiflexor, namely m. tibialis anterior, could not be part of the present investigation.

Table 3 shows that during mid-drive six subjects out of a total of eight (three females and three males) exhibited co-activation of m. biceps femoris and m. gastrocnemius; these two biarticular knee flexors are active during knee extension. The occurrences reported in Table 2 have been subjected to the final level of the systematic classification with the information offered by the joint kinetic analysis. The power curves revealed when the net moment power was concentrically extending the knee and allowed to determine how many subjects exhibited simultaneous concentric muscle activity and concentric power from the joint moment of force during the extension of the knee (see results in Table 4).

At the knee joint, according to the criteria delineated in Table 1, all the requirements are met for m. biceps femoris (in four out of eight subjects) and for m. gastrocnemius (in three out of eight subjects). There is then strong evidence for the function of these biarticular muscles to be paradoxical since they are both expected to flex the knee joint. When no concentric power was produced at the knee, m. gastrocnemius and m. biceps femoris were still active and shortening, thereby stabilizing the joint.

Another finding that came as a surprise is that m. rectus femoris, known as both a hip flexor and a knee extensor, was delivering extending power at the hip joint in three male and three female subjects during the late drive.

As suggested by the conjoint EMG activity of m. gastrocnemius and m. biceps femoris (from Table 3), there was also simultaneous contribution of both muscles to the extension of the knee (see Table 4). The original results reveal that this common occurrence took place in the same single female and two male subjects. So three subjects, out of eight, displayed this mechanical behavior.

Aside from the personal technique that comes into play during the extension of the knee in rowing, the anatomical differences between subjects may account for the non-homogeneous occurrence of paradoxical behavior amongst individuals. As pointed out by Rasch and Burke (1978), the sartorius muscle, for example, is a knee flexor in most individuals but a knee extensor in some. The same reverse function might apply to the actions of other biarticular muscles in the human leg.

Conclusion

This study was aimed at understanding the mechanics of the rowing motion at the muscle level. For this purpose a Gjessing rowing ergometer was instrumented with a force platform. The functional role of six major leg muscles was determined during the drive phase of the stroke with a classification system which took into account the myographic activity, the changes in muscle length, the directions of the joint angular velocities and the power from the net moments of force. According to this classification system, the biceps femoris and the gastrocnemius muscles emerged as paradoxical agonists during the extension of the knee in four males and three females out of a total of eight subjects. The rest of the drive time, these muscles were mainly used to stabilize the joint(s). A novel action has also been found for m. rectus femoris which appeared to act as a paradoxical agonist for hip extension in six out of eight subjects. The peculiar character of these observations might be accounted for by the reduced need for stabilization of the joints in ergometer rowing when compared to other activities. An important difference in the rowing of an ergometer has been depicted between the male and the female athletes tested; the moment power for the drive originated from the hip joint in the women whereas the men produced power at both the hip and the knee joints.

Suggestions for further research

It is evident that averaging the results between subjects would not have permitted the observations made in this study with regard to muscle function. According to the classification scheme, the probability that some elements of the lower extremity musculature function in a paradoxical fashion under certain circumstances has been proven to be high for some individuals. A greater number of subjects, a repetitive testing protocol (such as averaging over several strokes) applied to subjects that exhibit such a high probability and more stringent criteria in the classification system should be part of further research to ascertain the role of the leg biarticular muscles during knee extension. For the sport of rowing, a more in-depth examination of the pre-drive phase where the muscles are stretched and then active to absorb the momentum accumulated during the recovery phase might also provide valuable information with regard to the preparation of athletes; as depicted in Figure 6, the impulse during that time period is substantial. (This portion of the stroke was defined and looked at as part of the drive in this study as force was applied to the foot stretcher). Co-activation of the biarticular muscles of the lower segment should perhaps be seen as synergistic action. The notion of paradoxical action might ultimately disappear if the function of the multi-joint muscles is regarded conjointly with the action of other muscles. The muscles' theoretical role which, to date, has been dictated by single joint anatomical characteristics, might therefore be revised in the future.

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Appendix A

Muscle-Tendon Length Determination

Muscle-Tendon Length Determination

This appendix shows how the length of each muscle-tendon unit was estimated from anthropometric measurements and cinematographical records. The span of biceps femoris, gastrocnemius, gluteus maximus, rectus femoris, soleus and vastus lateralis was determined with equations developed by Frigo and Pedotti (1978) and modified by Hubley (1981). From each image of the cinefilm, the instant length was computed and was used to calculate the rate of change in muscle-tendon length.

In all diagrams, ***RHT*** stands for real height and represents the standing height of the subject (in centimetres) and ***L*** refers to muscle length. The hip (N_1), knee (N_2) and ankle (N_3) angles were calculated from the data digitized from the cinefilm according to the following diagram (figure 14).

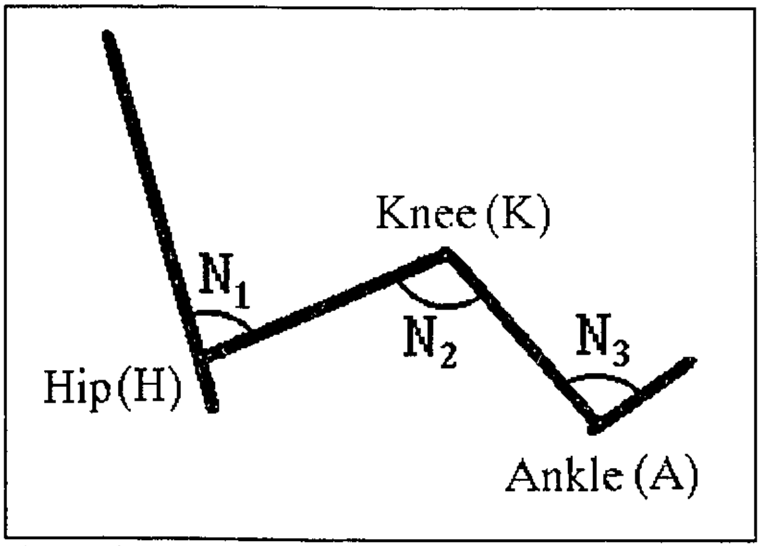


Figure 14. Measured angles from cinefilm.

Biceps Femoris (long head)

Origin (O): Medial facet of the ischial tuberosity.

Insertion (I): Lateral condyle of the tibia and head of the fibula.

N_1 = hip angle = $\theta_{pelvis} + \theta_{thigh}$

N_2 = knee angle

$\gamma = 152°$

OH = 6.3 cm

KF = 2.5 cm

KI = 6.7 cm

HK = 0.2320 · RHT

$\angle OHK = 360° - \gamma - N_1$

$OK = \sqrt{(HK)^2 + (OH)^2 - 2 \cdot (HK) \cdot (OH) \cdot \cos \angle OHK}$

$\angle OKH = \arcsin [(OH \cdot \sin \angle OHK) / OK]$

$\angle OKI = N_2 - \angle OKH$

$OI = \sqrt{(OK)^2 + (KI)^2 - 2 \cdot (OK) \cdot (KI) \cdot \cos \angle OKI}$

$\angle FKI = N_2 - 90°$

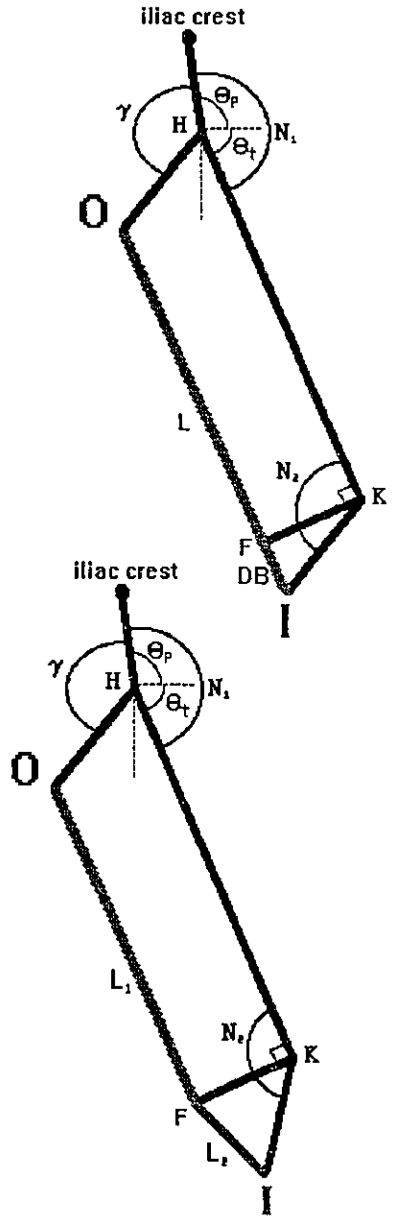
$\angle FIK = \arcsin [(OK \cdot \sin \angle OKI) / OI]$

$\angle IFK = 180° - \angle FKI - \angle FIK$

$IF = (KI \cdot \sin \angle FIK) / \sin \angle IFK$

When $IF \geqslant KF$:

$$\boxed{L = OI}$$



When $IF < KF$:

$L_1 = \sqrt{(OK)^2 - (KF)^2}$

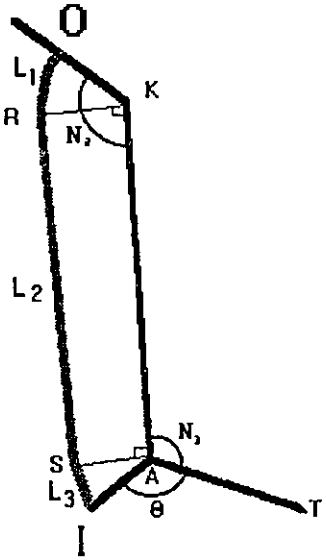
$L_2 = \sqrt{(KF)^2 + (KI)^2 - 2 \cdot (KF) \cdot (KI) \cdot \cos \angle FKI}$

$$\boxed{L = L_1 + L_2}$$

Figure 15. Geometrical muscle-tendon model for the determination of the length of m. biceps femoris.

Gastrocnemius

Origin (O) : Posterior head of the femoral condyles.
Insertion (I) : Achilles tendon (on the calcaneus).



N_2 = knee angle

N_3 = ankle angle

$$KR = 0.0218 \cdot RHT$$

$$AI = 0.0376 \cdot RHT$$

$$AS = KR$$

$$\theta = 120^\circ$$

$$L_2 = KA = 0.2470 \cdot RHT$$

$$\angle OKR = N_2 - 90^\circ$$

$$L_1 = (\angle OKR / 360^\circ) \cdot 2\pi \cdot (KR) = (N_2 - \pi/2) \cdot KR$$

$$\angle IAK = 360^\circ - N_3 - \theta = 240^\circ - N_3$$

$$\angle IAS = \angle IAK - 90^\circ$$

$$L_3 = \sqrt{[(AS)^2 + (AI)^2 - 2 \cdot (AS) \cdot (AI) \cdot \cos\angle IAS]}$$

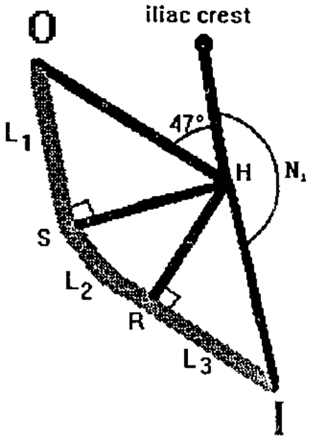
$$\boxed{L = L_1 + L_2 + L_3}$$

Figure 16. Geometrical muscle-tendon model for the determination of the length of m. gastrocnemius.

Gluteus Maximus

Origin (O) : Outer surface of the illium.

Insertion (I) : Posterior aspect of the femur.

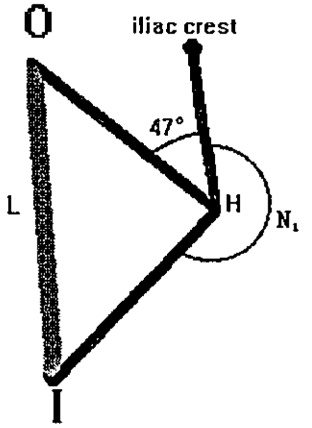


N_1 = hip angle
$OH = 8.8\,\text{cm}$
$HI = 14.8\,\text{cm}$
$HS = HR = 4.6\,\text{cm}$
$\angle OHS = \arccos(HS / OH) = 58.5°$
$\angle IHR = \arccos(HR / HI) = 71.9°$
$\angle SHR = 360° - 47° - \angle OHS - \angle IHR - N_1$
$\angle SHR = 360° - 182.6° - N_1$

When $\angle SHR > 0$:

$L_1 = \sqrt{(OH)^2 - (HS)^2}$
$L_2 = (\angle SHR / 360°) \cdot (2\pi) \cdot (HS)$
$L_3 = \sqrt{(HI)^2 - (HR)^2}$

$$\boxed{L = L_1 + L_2 + L_3}$$



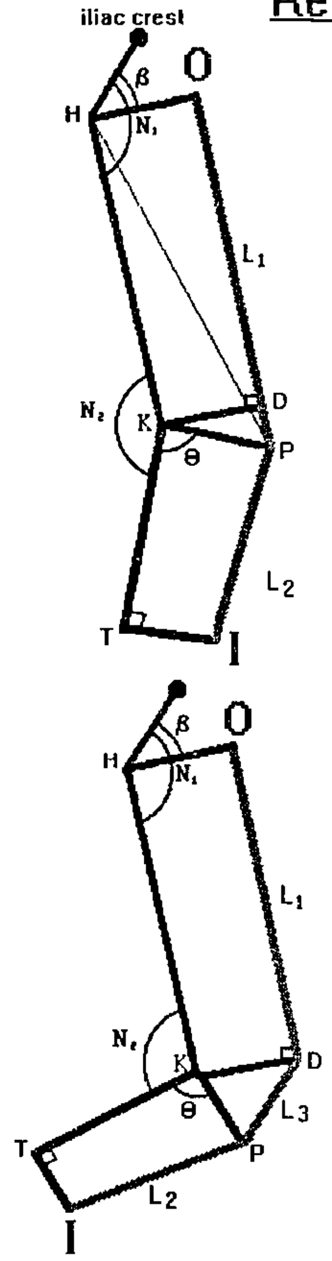
When $\angle SHR = 0$:

$OHI = 360° - N_1 - 47°$

$$\boxed{L = \sqrt{(HI)^2 + (OH)^2 - 2 \cdot (HI) \cdot (OH) \cos \angle OHI}}$$

Figure 17. Geometrical muscle-tendon model for the determination of the length of m. gluteus maximus.

Rectus Femoris



Origin [O] : Anterior inferior spinous process on the ilium.

Insertion [I] : Patellar tendon.

N_1 = hip angle
N_2 = knee angle
$\beta = 48°$
$L_2 = 0.0455 \cdot RHT$
$HK = 0.2320 \cdot RHT$
$PK = 0.0242 \cdot RHT$
$OH = 0.0273 \cdot RHT$
$DK = 0.0212 \cdot RHT$
$\angle TKP = 83°$
$\angle HKP = 360° - N_2 - \angle TKP$
$PH = \sqrt{[(HK)^2 + (PK)^2 - 2 \cdot (HK) \cdot (PK) \cdot \cos \angle HKP]}$
$\angle PHK = \arcsin \left[\frac{(PK) \cdot \sin(\angle HKP)}{PH} \right]$
$\angle OHP = N_1 - \angle PHK - \beta$
$OP = \sqrt{[(OH)^2 + (HP)^2 - 2 \cdot (OH) \cdot (HP) \cdot \cos \angle OHP]}$
$L_1 = OP$

When $N_2 > 151°$:

$$\boxed{L = L_1 + L_2}$$

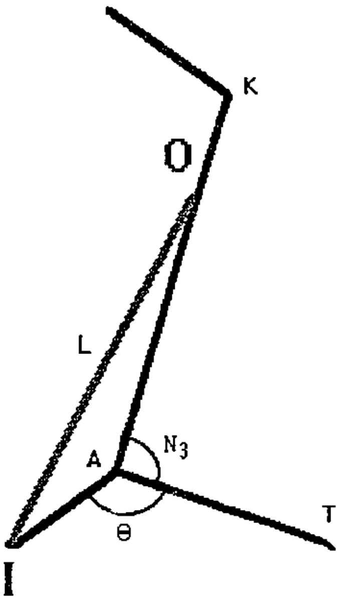
When $N_2 < 151°$:

$\angle OHK = N_1 - \beta$
$OK = \sqrt{[(OH)^2 + (HK)^2 - 2 \cdot (OH) \cdot (HK) \cdot \cos \angle OHK]}$
$\angle OKH = \arcsin \left[\frac{(OH) \cdot \sin \angle OHK}{OK} \right]$
$\angle OKD = \arccos (DK / OK)$
$L_1 = \sqrt{[(OK)^2 - (DK)^2]}$
$\angle HKD = \angle OKH + \angle OKD$
$\angle DKP = 360° - \angle TKP - N_2 - \angle HKD$
$L_3 = \sqrt{[(DK)^2 + (PK)^2 - 2 \cdot (DK) \cdot (PK) \cdot \cos \angle DKP]}$

$$\boxed{L = L_1 + L_2 + L_3}$$

Figure 18. Geometrical muscle-tendon model for the determination of the length of m. rectus femoris.

Soleus



Origin (O) : Posterior head of the fibula and oblique line of the tibia.

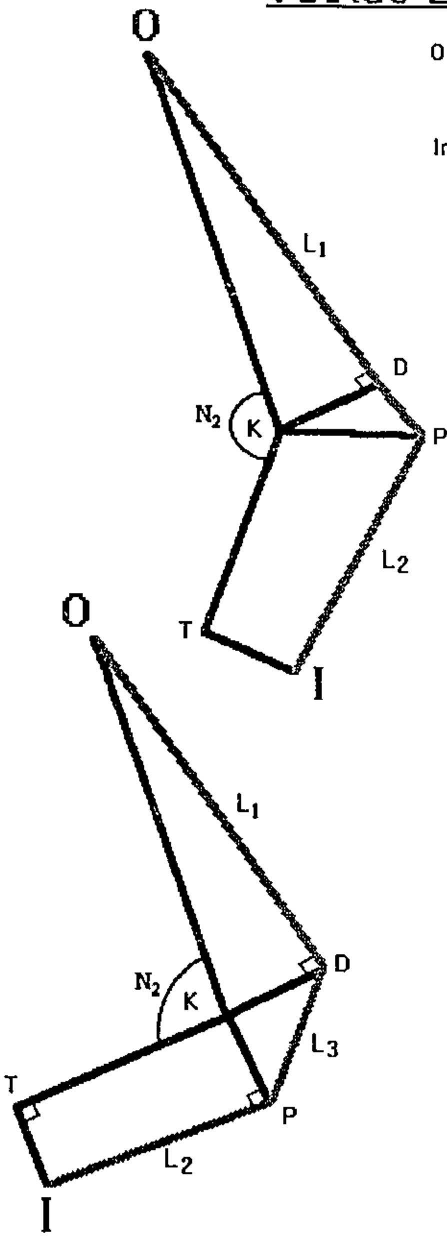
Insertion (I) : Achilles tendon (on the calcaneus).

N_3 = ankle angle
OA = 0.1920·RHT
AI = 0.038·RHT
$\theta = 120°$
$\angle OAI = 360° - N_3 - \theta$

$$\boxed{L = \sqrt{[(OA)^2 + (AI)^2 - 2 \cdot (OA) \cdot (AI) \cos \angle OAI]}}$$

Figure 19. Geometrical muscle-tendon model for the determination of the length of m. soleus.

Vastus Lateralis



Origin (O): Upper half of the anterior intertrochanteric line, outer lip of the linea aspera.
Insertion(I): Patellar tendon.

N_2 = knee angle
$\angle TKP = 83°$
$L_2 = 0.0455 \cdot RHT$
$OK = 0.1520 \cdot RHT$
$KT = 0.0519 \cdot RHT$
$PK = 0.0182 \cdot RHT$
$DK = 0.0212 \cdot RHT$
$\angle OKP = 360° - TKP - N_2$
$OP = L_1$
$L_1 = \sqrt{[(OK)^2 + (PK)^2 - 2 \cdot (OK) \cdot (PK) \cos\angle OKP]}$

When $N_2 \geqslant 151°$:

$\boxed{L = L_1 + L_2}$

When $N_2 < 151°$:

$\angle OKD = 82°$
$\angle DKP = 360° - \angle TKP - N_2 - \angle OKD$
$L_1 = \sqrt{(OK)^2 + (DK)^2}$
$L_3 = \sqrt{[(DK)^2 + (PK)^2 - 2 \cdot (DK) \cdot (PK) \cos\angle DKP]}$

$\boxed{L = L_1 + L_2 + L_3}$

Figure 20. Geometrical muscle-tendon model for the determination of the length of m. vastus lateralis.

Appendix B

Individual Results

Individual Results

The following figure (21) is a representative stick diagram of the whole rowing motion. The remainder of this Appendix presents plots of the curves obtained from every subject and allows a visual comparison of the results between subjects.

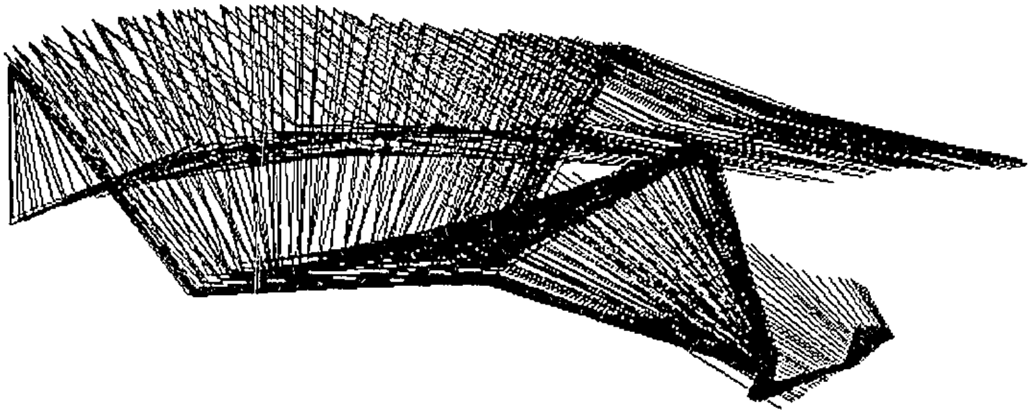


Figure 21. Stick figure of the kinematic pattern and stretcher reaction force for the drive and the recovery — male ergometer rowing — *rmbs*.

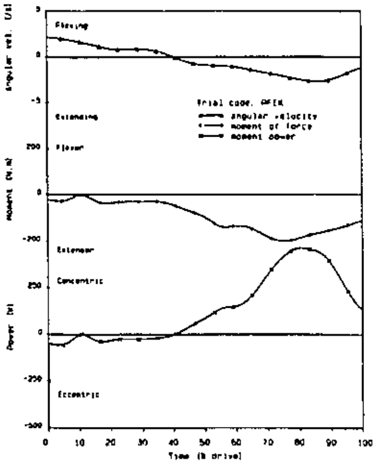


Figure 22. Hip angular velocity, net joint moment of force and power — female rower.

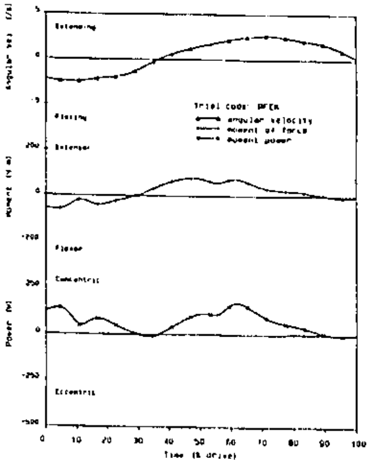


Figure 23. Knee angular velocity, net joint moment of force and power — female rower.

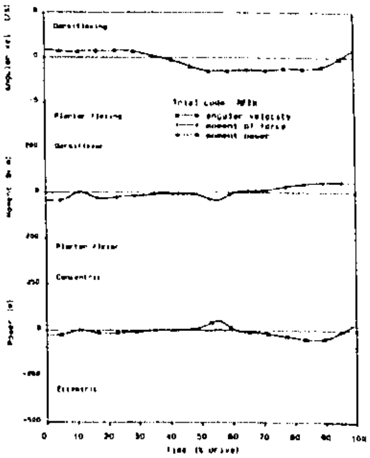


Figure 24. Ankle angular velocity, net joint moment of force and power — female rower.

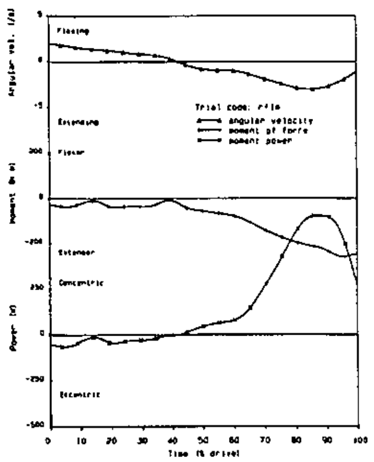


Figure 25. Hip angular velocity, net joint moment of force and power — female rower.

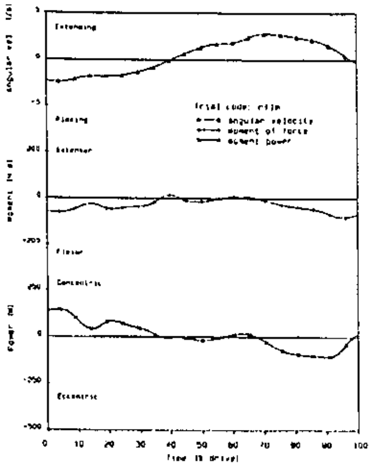


Figure 26. Knee angular velocity, net joint moment of force and power — female rower.

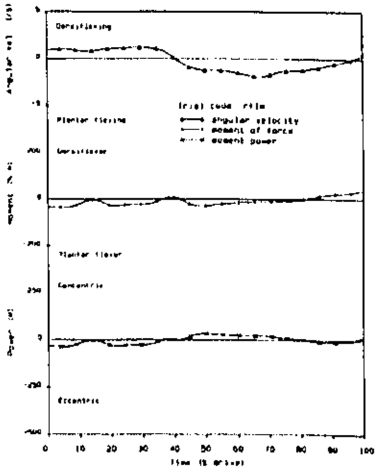


Figure 27. Ankle angular velocity, net joint moment of force and power — female rower.

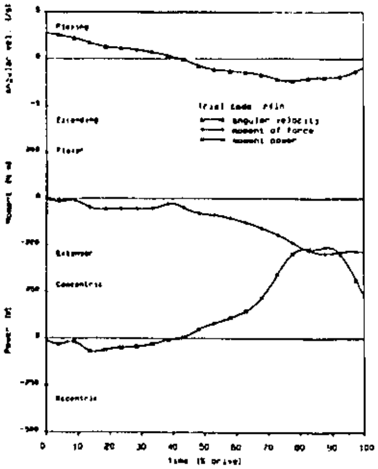


Figure 28. Hip angular velocity, net joint moment of force and power — female rower.

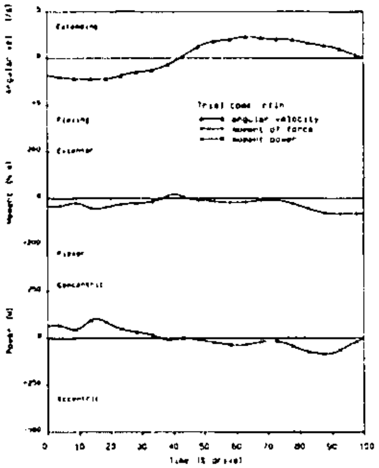


Figure 29. Knee angular velocity, net joint moment of force and power — female rower.

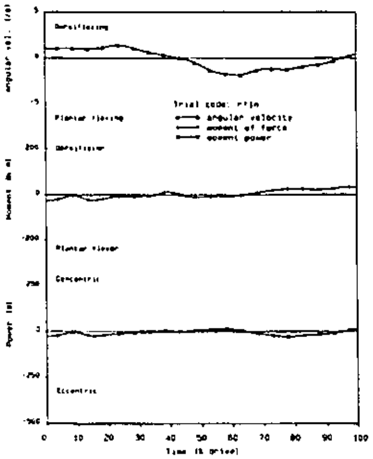


Figure 30. Ankle angular velocity, net joint moment of force and power — female rower.

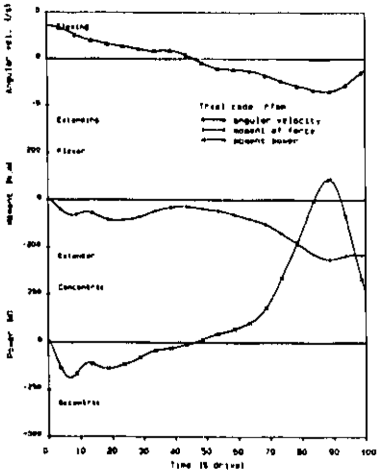


Figure 31. Hip angular velocity, net joint moment of force and power — female rower.

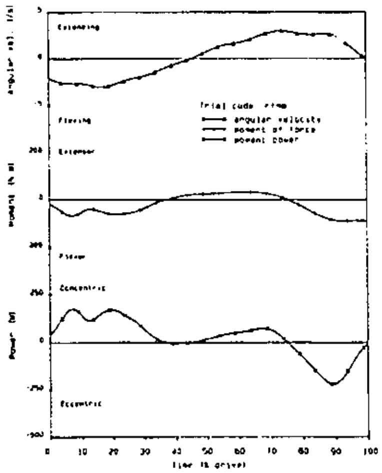


Figure 32. Knee angular velocity, net joint moment of force and power — female rower.

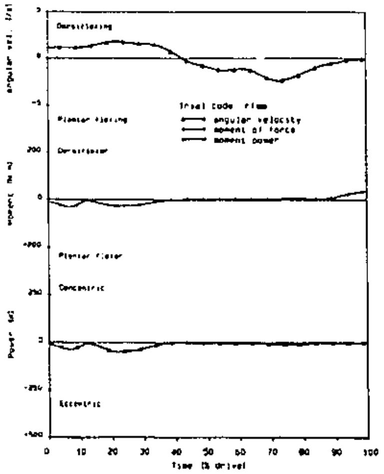


Figure 33. Ankle angular velocity, net joint moment of force and power — female rower.

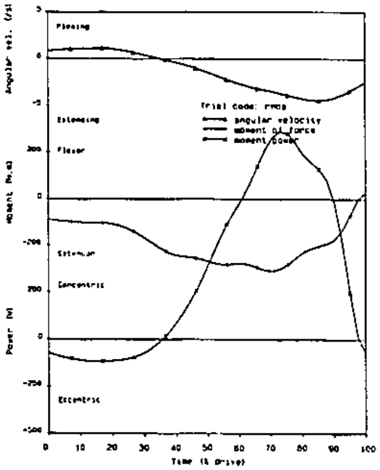


Figure 34. Hip angular velocity, net joint moment of force and power — male rower.

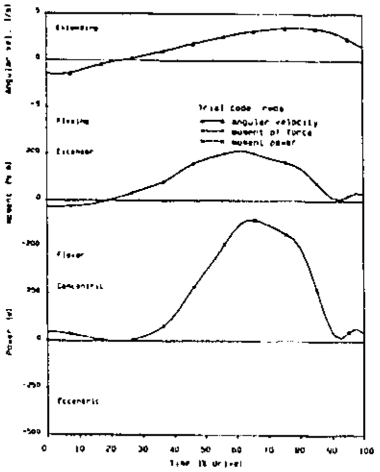


Figure 35. Knee angular velocity, net joint moment of force and power — male rower.

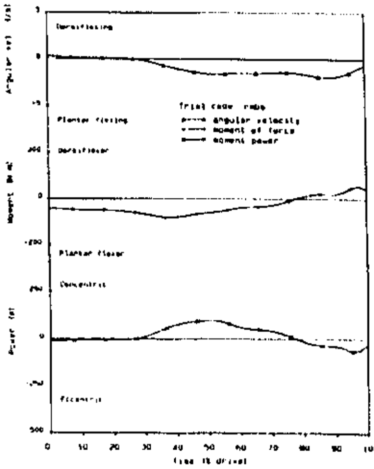


Figure 36. Ankle angular velocity, net joint moment of force and power — male rower.

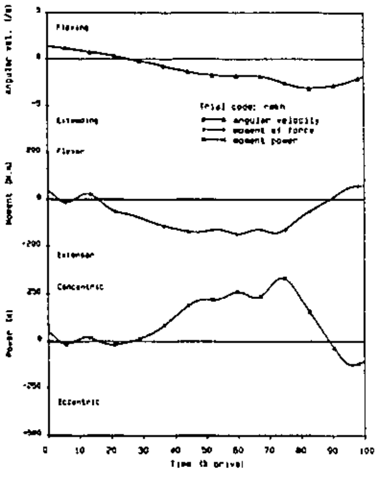


Figure 37. Hip angular velocity, net joint moment of force and power — male rower.

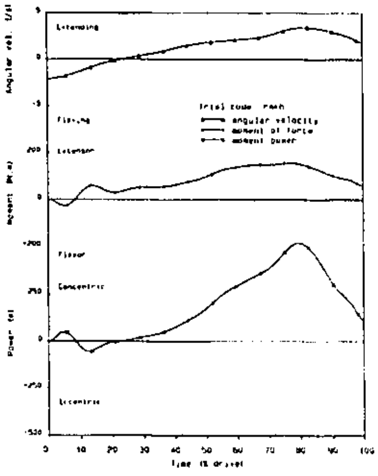


Figure 38. Knee angular velocity, net joint moment of force and power — male rower.

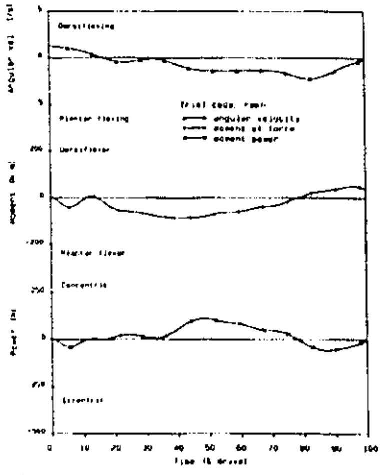


Figure 39. Ankle angular velocity, net joint moment of force and power — male rower.

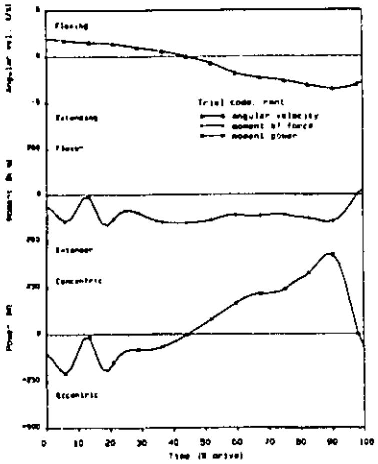


Figure 40. Hip angular velocity, net joint moment of force and power — male rower.

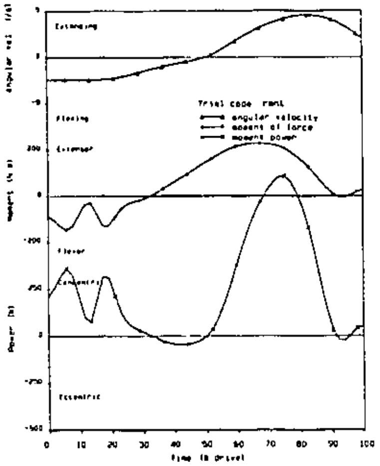


Figure 41. Knee angular velocity, net joint moment of force and power — male rower.

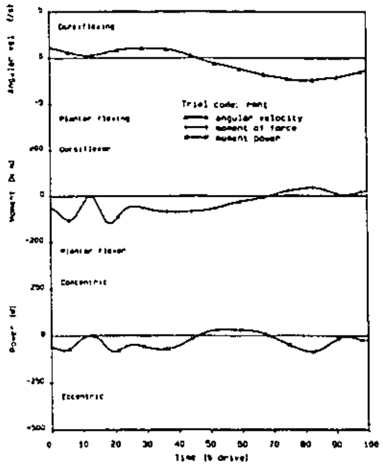


Figure 42. Ankle angular velocity, net joint moment of force and power — male rower.

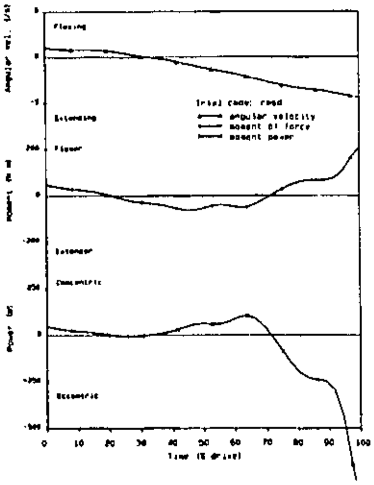


Figure 43. Hip angular velocity, net joint moment of force and power — male rower.

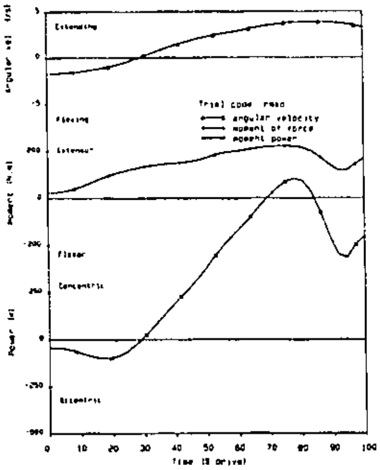


Figure 44. Knee angular velocity, net joint moment of force and power — male rower.

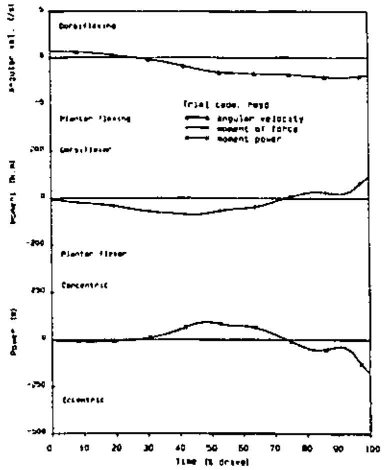


Figure 45. Ankle angular velocity, net joint moment of force and power — male rower.

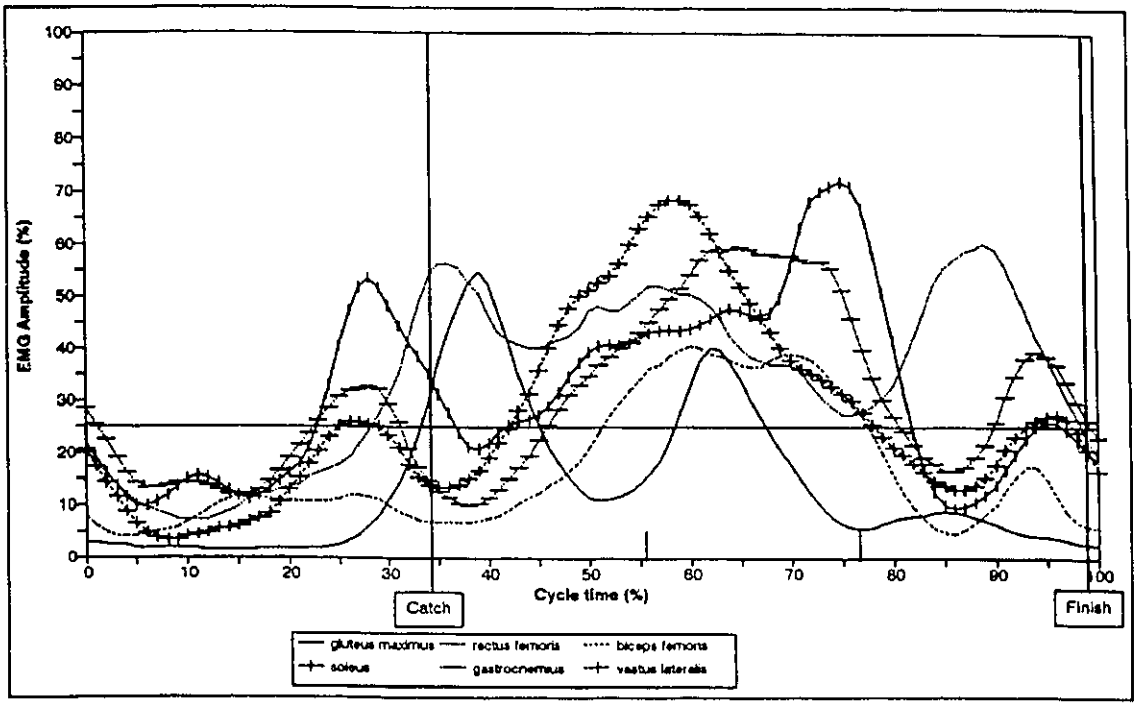


Figure 46. Linear envelope EMG averaged over ten cycles — female subject — rfek.

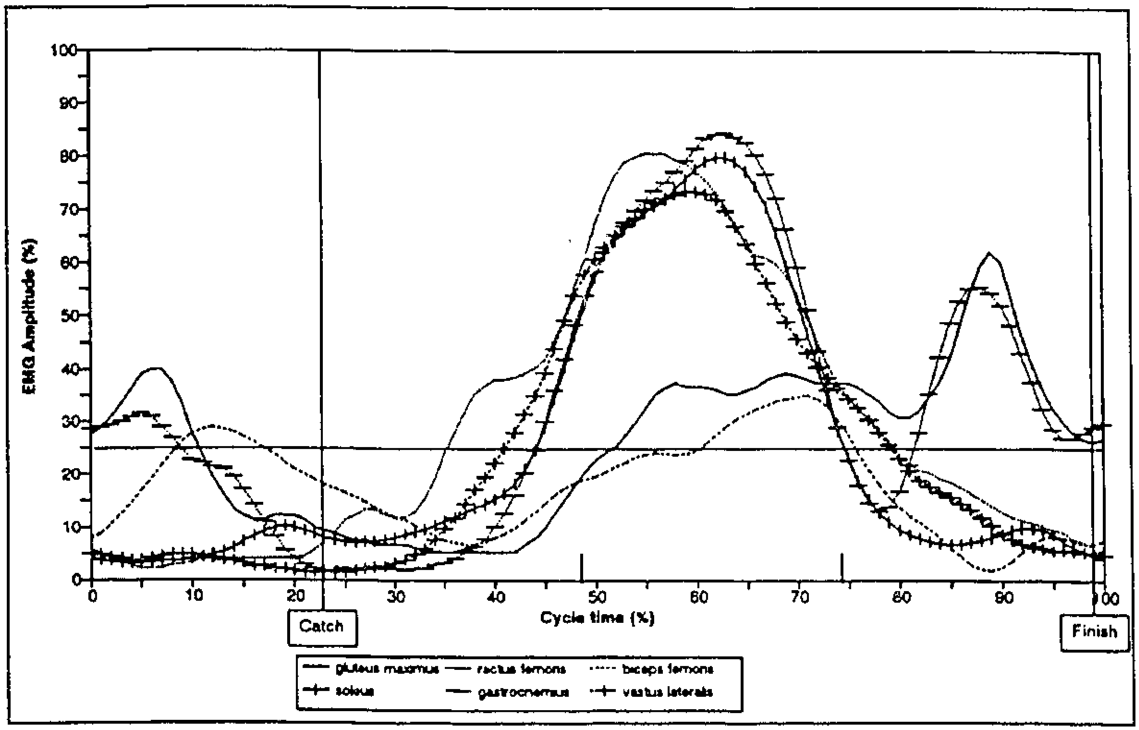


Figure 47. Linear envelope EMG averaged over ten cycles — female subject — rflm.

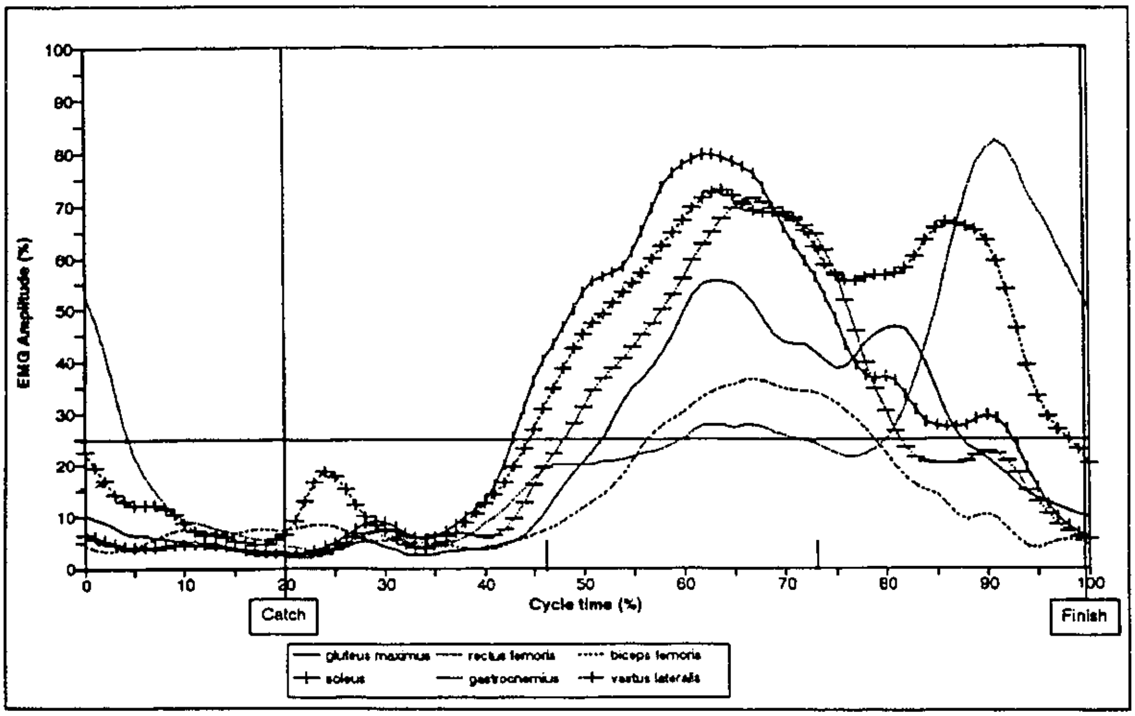


Figure 48. Linear envelope EMG averaged over ten cycles — female subject — rfln.

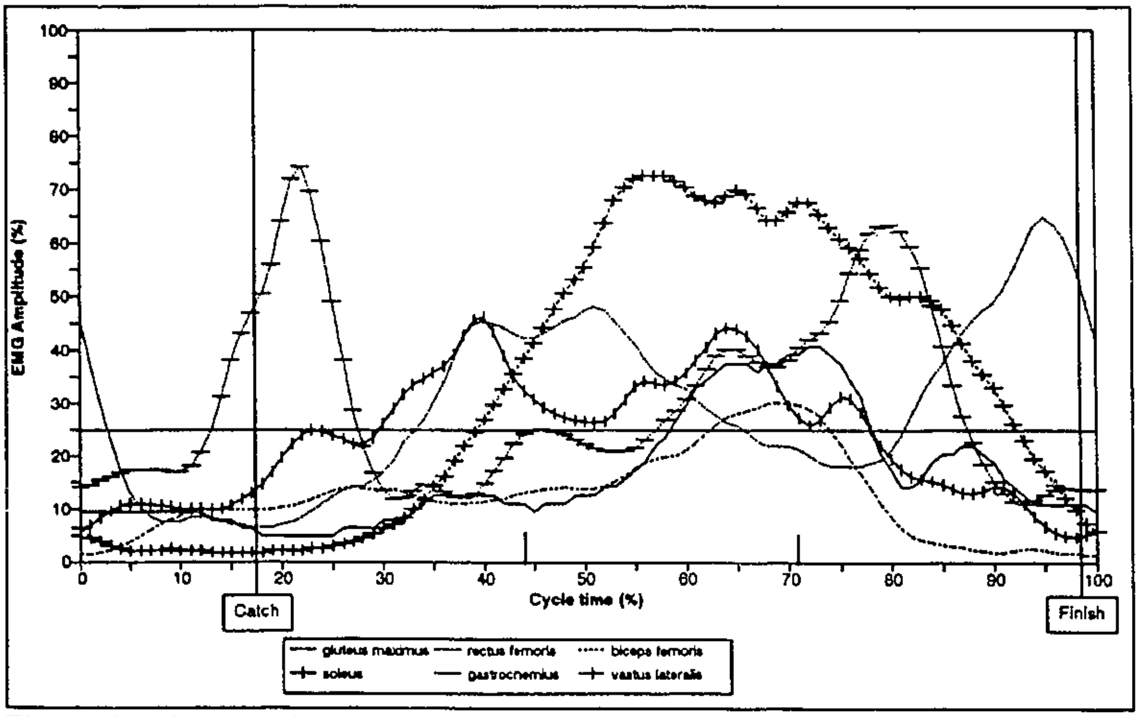


Figure 49. Linear envelope EMG averaged over ten cycles — female subject — rfmm.

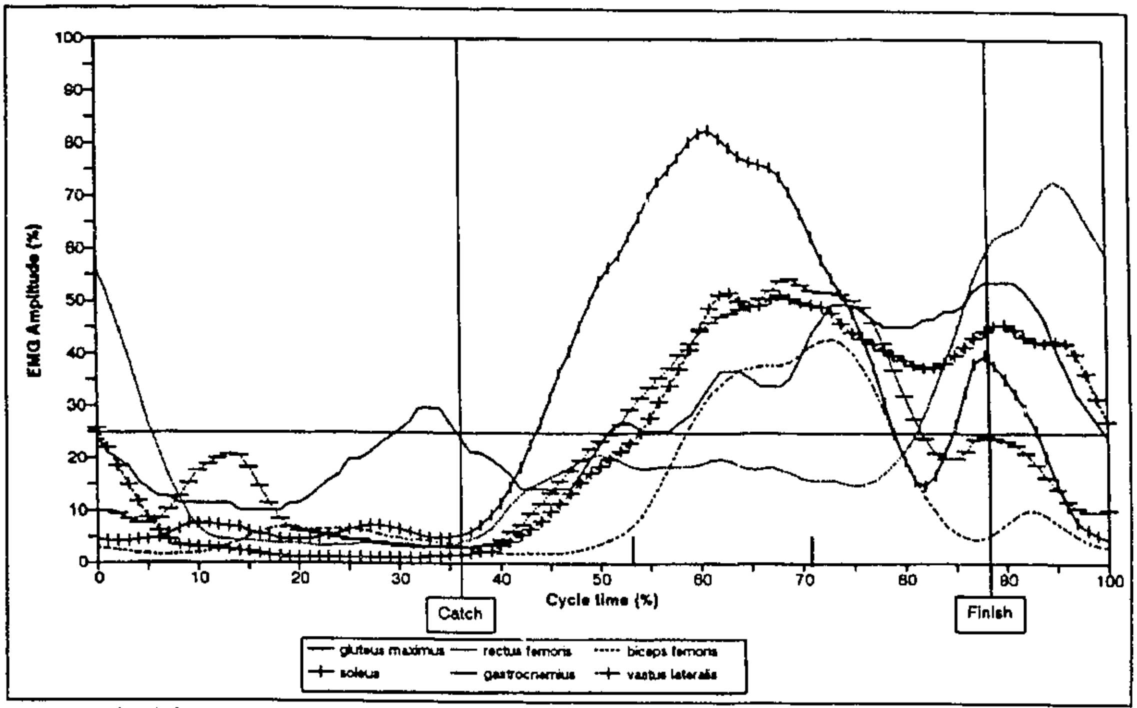


Figure 50. Linear envelope EMG averaged over ten cycles — male subject — rmdh.

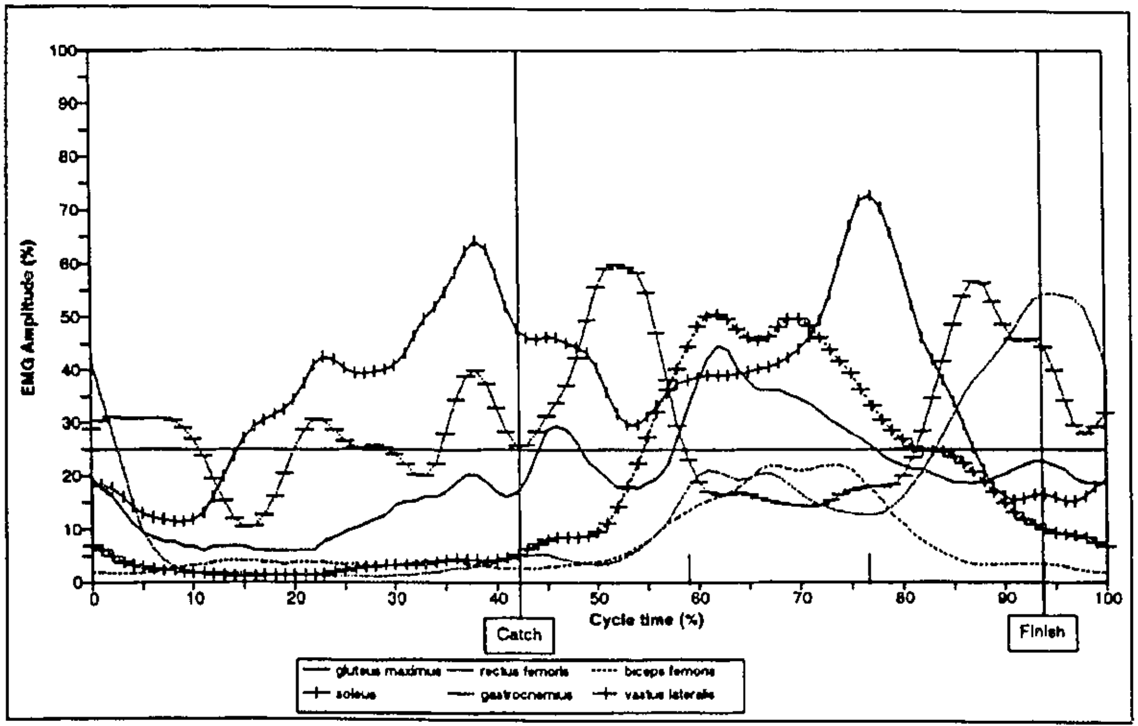


Figure 51. Linear envelope EMG averaged over ten cycles — male subject — rmkh.

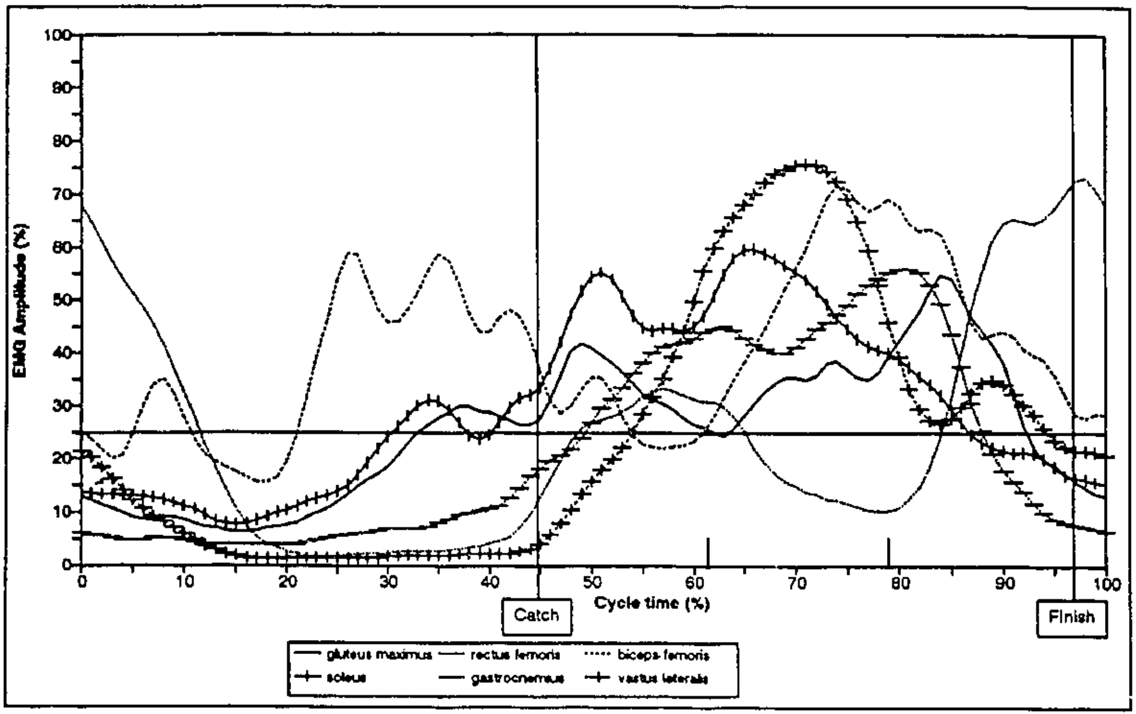


Figure 52. Linear envelope EMG averaged over ten cycles — male subject — rmnt.

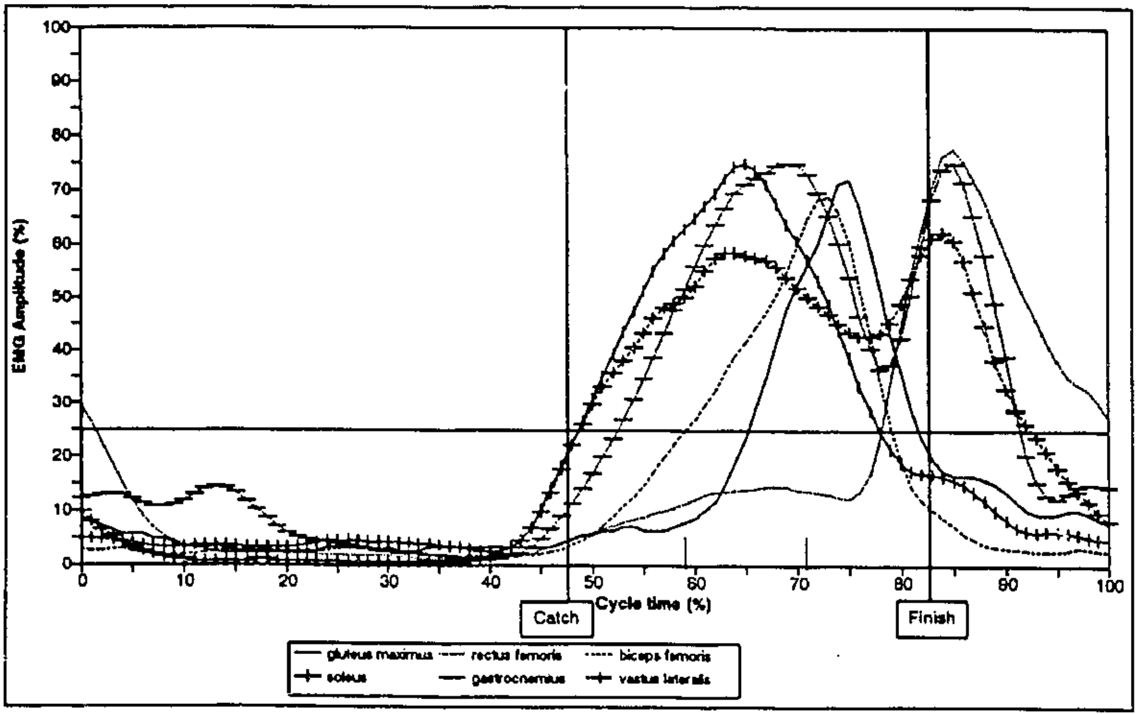


Figure 53. Linear envelope EMG averaged over ten cycles — male subject — rmsd.

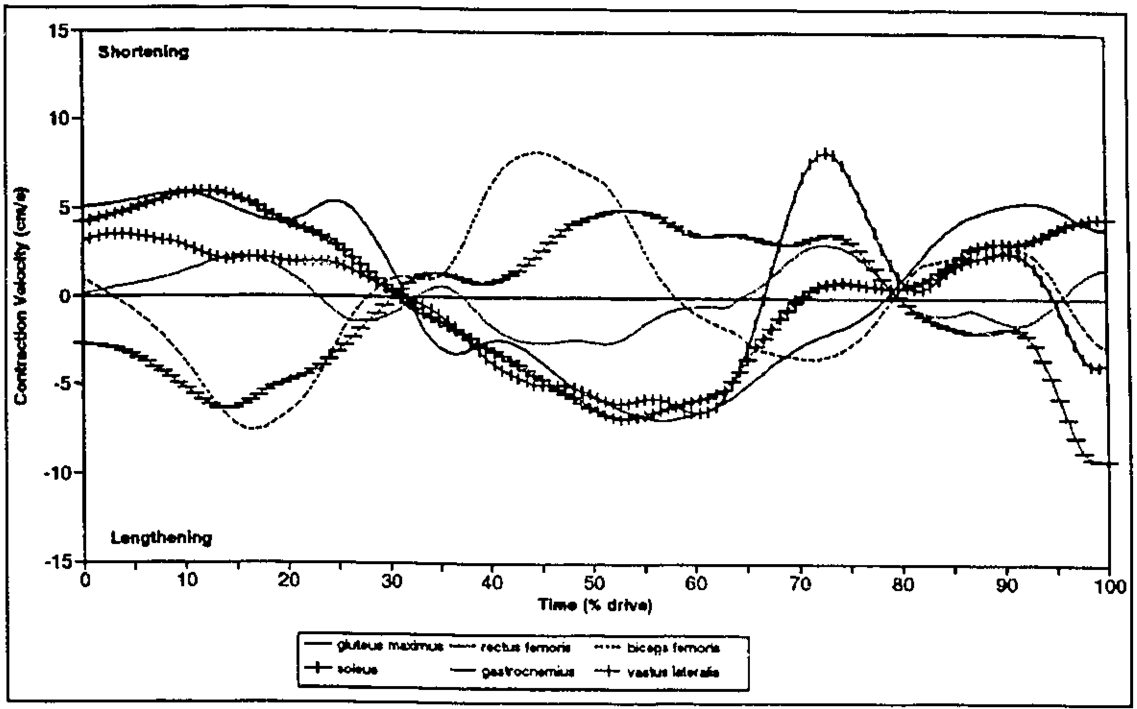


Figure 54. Contraction velocity of the six muscles during the drive — female subject — rfln.

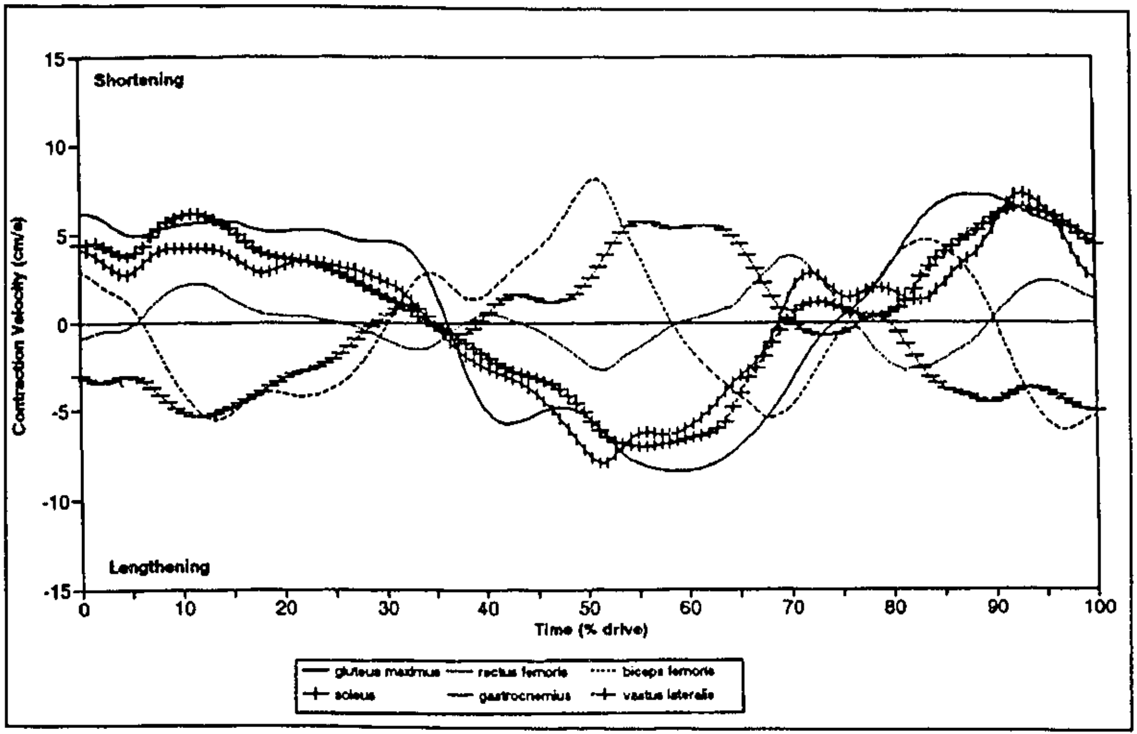


Figure 55. Contraction velocity of the six muscles during the drive — female subject — rflm.

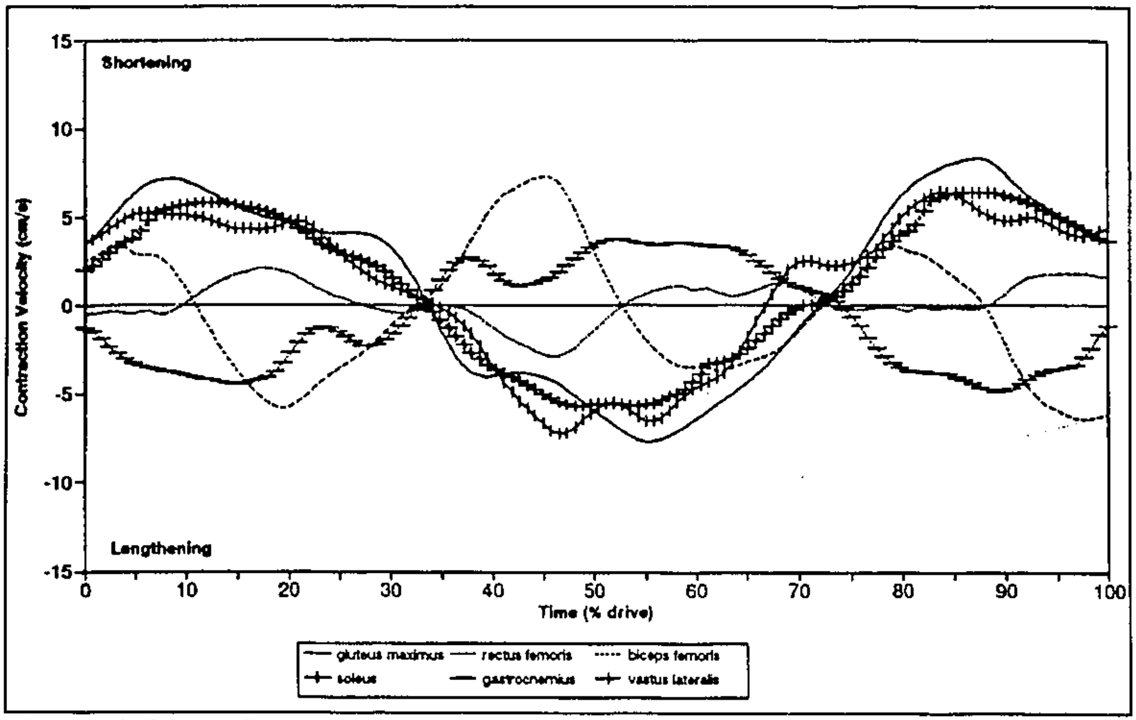


Figure 56. Contraction velocity of the six muscles during the drive — female subject — rfln.

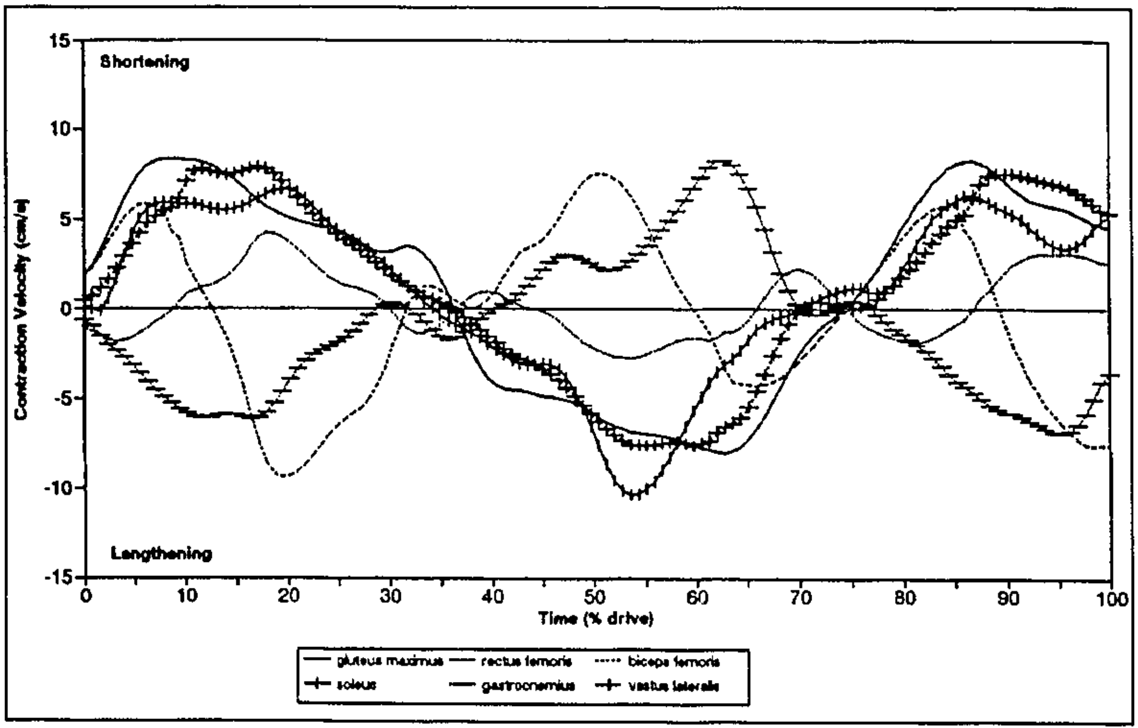


Figure 57. Contraction velocity of the six muscles during the drive — female subject — rfln.

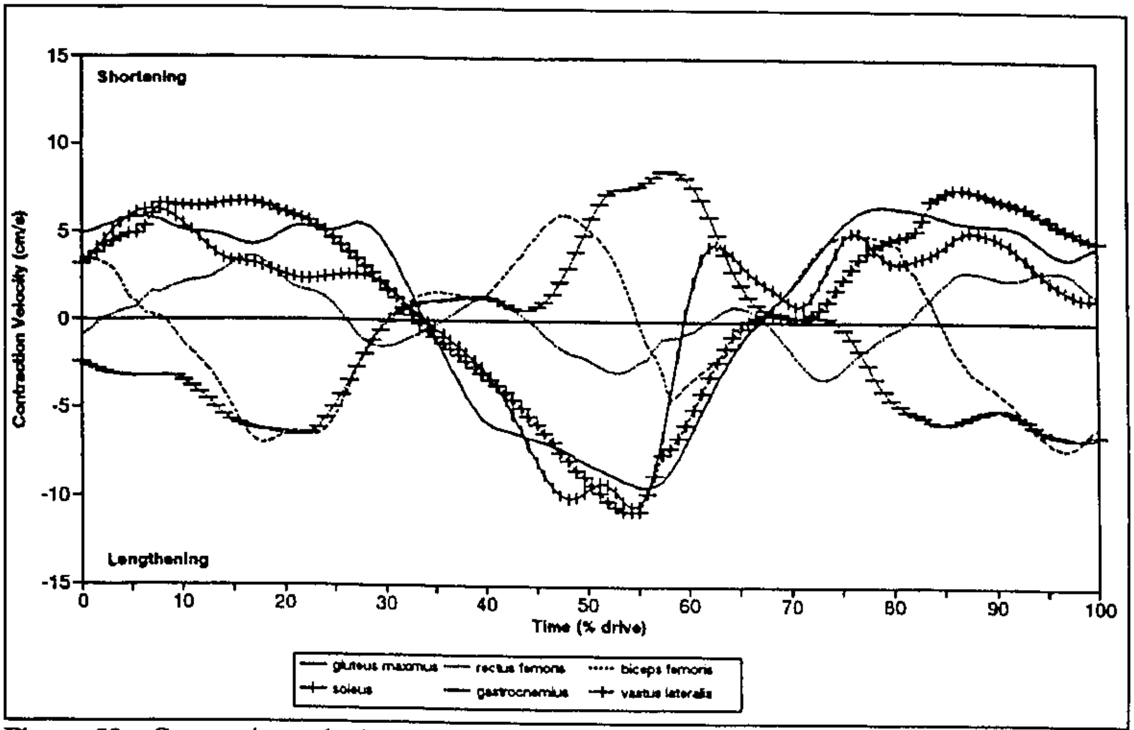


Figure 58. Contraction velocity of the six muscles during the drive — male subject — rmdh.

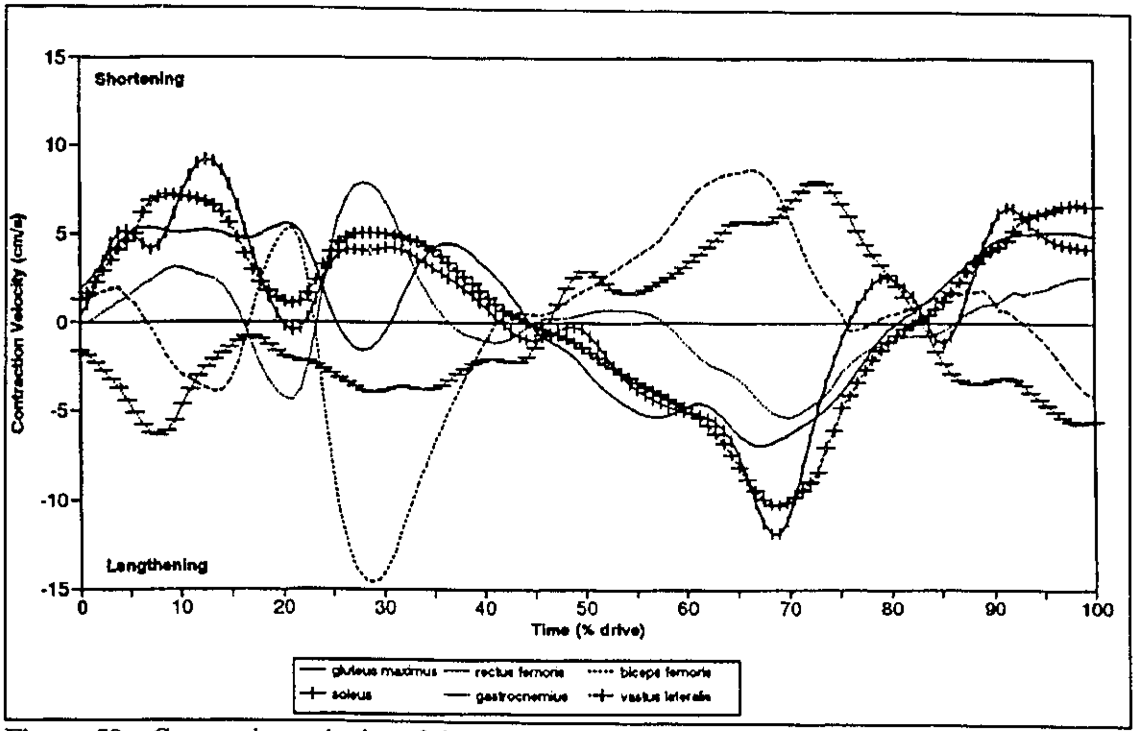


Figure 59. Contraction velocity of the six muscles during the drive — male subject — rmkh.

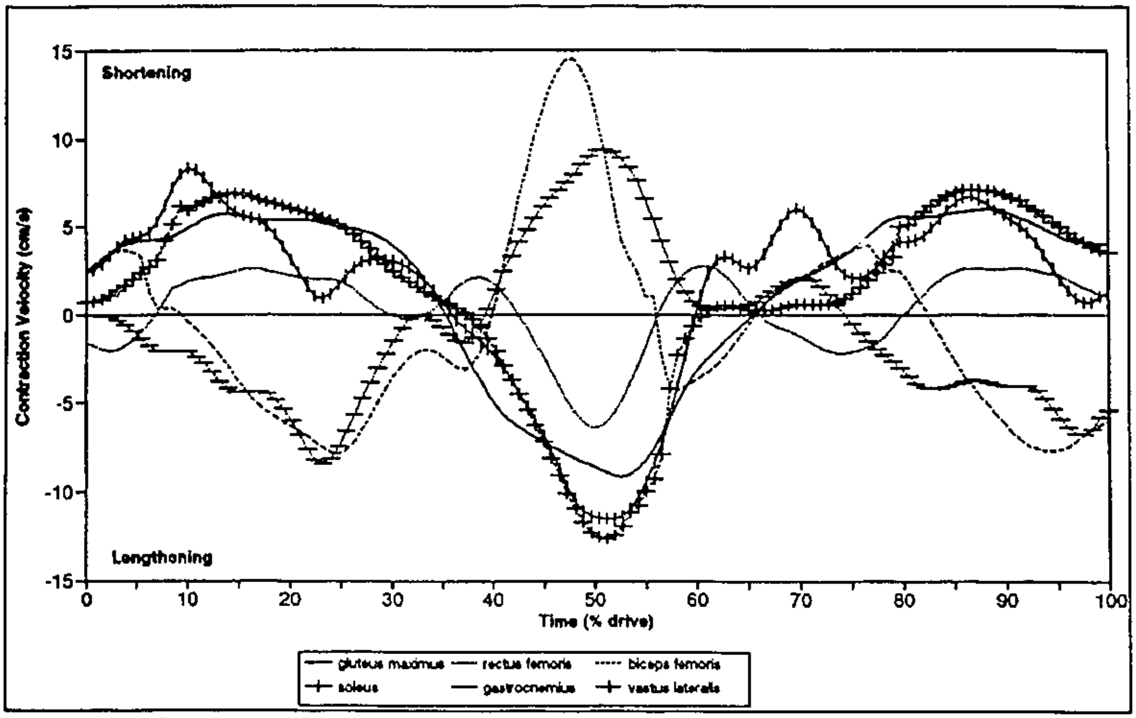


Figure 60. Contraction velocity of the six muscles during the drive — male subject — rmnt.

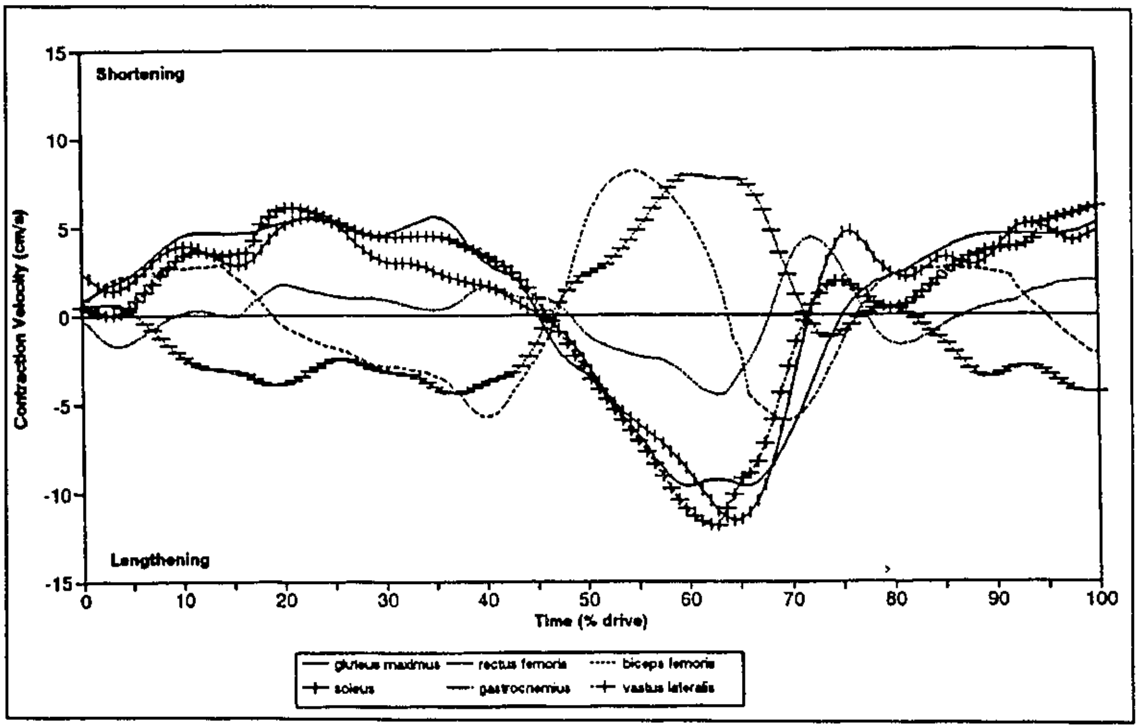


Figure 61. Contraction velocity of the six muscles during the drive — male subject — rmsd.

Appendix C

Consent Form

SCHOOL OF HUMAN KINETICS THESIS RESEARCH CONSENT FORM

The following is to inform you about the study you are volunteering to participate in and about what is expected from yourself as a subject. It also describes the potential risks associated with the testing procedure and your rights as a voluntary participant.

The purpose of the study is to examine the function of the leg muscles during ergometer rowing. Its aim is to determine the role of the main muscles, particularly the muscles that cross two joints, involved in the rowing motion.

One training session will precede the test session to ensure familiarization of the athlete with the ergometer. It will consist of rowing the Gjessing ergometer four times, for at least two minutes per bout, with two minutes of rest between the bouts. There will be at least one day between each session.

The test session will include anatomical measurements and the placement of surface electrodes to measure the electrical activity of the muscles (EMG) during the test. Anatomical measurements imply that various body dimensions, such as body weight, standing height, and the length of body parts (trunk, thigh, foreleg, foot) will be measured. The preparation of the skin (hair shaving, cleaning with rubbing alcohol) prior to the application of the EMG electrodes may involve a momentary burning sensation at each of the 13 sites on the leg. The determination of maximal EMG levels will entail the simulation of the rowing motion against a fixed object and will require maximal muscle contraction for a few seconds. Reflective markers (self-adhesive tape) will be applied onto the skin to locate the centre of rotation of the joints. To facilitate this task, some points may be traced directly on the skin with a pen. Subjects are expected to wear shorts and a tee-shirt.

The test itself will begin after a warm-up whose duration will be determined by the subject. The data collection will take place over a period of approximately 30 seconds.

I, ________________________(printed name), authorize Yves Fortin (237-9719 or 564-9105) of the School of Human Kinetics (Biomechanics Laboratory, room 319, 125 University Private, Montpetit Hall), University of Ottawa, to administer and conduct an exercise test that consists of rowing a Gjessing ergometer at a submaximal workload. The test will be carried out under the supervision of Dr. D.G.E. Robertson (564-9130). This study has been approved by the Human Research Ethics Committee (Dr. M. Loyer, chair, 787-6707).

I may experience some physical discomfort and fatigue similar to what is experienced while rowing on the water. I recognize that there are potential risks to some individuals performing an exercise test such as lightheadedness, fainting, and, very rarely, heart attacks. Rowing an ergometer could subject one to back injury, particularly if not done properly. I do not suffer from any chronic medical problem and it is my responsibility to inform the testing personnel of any injury, illness, infection, undue fatigue or other condition which would prevent me from fully participating in these sessions.

All information collected will be kept confidential and presented in an anonymous form in the final report. I may refuse to take off my clothing and my shoes or to perform the tasks that the experimenter requests without penalty or discrimination. I also understand that I have the right to withdraw from this study at any time.

I have read the above comments and wish to proceed with the biomechanical evaluation.

NAME:________________________

WITNESS:________________________

(Signature)

DATE:__________________

Appendix D

Review of Literature

Review of Literature

The roles of two-joint muscles

The initial assessment of the lower limb's two-joint muscle action should be attributed to Lombard (1903a,b). He originally proposed the concept of tendon action of biarticular muscles. Also according to Lombard (1903a) the antagonist biarticular muscles of the thigh could, during cocontraction, act as single-joint antagonistic muscles when one of the two joints involved is fixed. When both joints are free to move, however, both muscles would reinforce each other and "pseudo antagonism" would take place. Looking at the mechanical advantage at the hip and knee, Lombard noted that the lever arms for extension must be greater than those for flexion. This led him to postulate what is known as ***Lombard's paradox*** (1903b): "A two-joint muscle may act as an extensor of the joint of which it is a flexor". Applied to the lower segment, it suggests that cocontraction of the antagonist biarticular muscles of the thigh cause simultaneous extension at the hip and knee. Lombard and Abbott (1907) substantiated this theory using the leg of the frog.

Elftman (1939b) considered the tendon action of taut muscles, described by Cleland (1867) as ligamentous and by Rasch and Burke (1978) as belt-like action of two-joint muscles, like a way of transmitting energy in human locomotion. This principle had already been described in details by Cleland as early as 1867. It has to be underlined that the tendon-action of biarticular muscles and Lombard's paradox are two different entities. The former describes force transfer within a closed loop, regardless of the length of the moment arms at the muscles' origins and insertions while Lombard's paradox requires mechanical advantage for flexion or extension at each joint. Elftman also quantified the mechanical advantage at the knee and hip joints in giving representative moment arm length values for both extension and flexion. In a representative individual, those length are 3.9 cm for extension (rectus femoris) *versus* 6.7 cm for flexion (hamstrings) at the hip and 4.4 cm for extension *versus* 3.4 cm for flexion at the knee. These values attest that one of Lombard's paradox requirements-the lever arms-is fulfilled anatomically. (Bock [1968] mentioned that two-joint muscles generally have longer moment arms than one-joint muscles.)

Although it has not yet been observed in humans, Markee *et al.*(1955) reported that both ends of a two-joint muscle in dogs could contract independently. The authors also proposed that the leg biarticular muscles would prevent excessive sliding at the knee joint and, thus, serve as stabilizers. Regarding the single-joint action of biarticular muscles, Basmajian (1957) refuted these findings. From the results of an EMG study of isometric positions involving rectus femoris, semitendinosus and semimembranosus on 21 human subjects, Basmajian concluded that the belly of two-joint muscles acts as a unit. Fujiwara and Basmajian (1975) came to the same conclusion from comparing the EMG activity of two-joint muscles from ten subjects during isolated mono- and bi-articular isometric and isotonic combinations. The study also revealed that inhibition takes place in the antagonistic coactivity of the rectus femoris and the medial hamstring, which may discredit the occurrence of Lombard's paradox. To provide further insight to these results, a similar investigation has been conducted by Kazai, Kumamoto, Yamashita, Maruyama and Tokuhara (1978) on five subjects. As in Fujiwara's and Basmajian's study, reciprocal inhibition was found to be a plausible explanation of decreased activity during cocontraction. These investigators also reported that the role of two-joint muscles in joint movements has no set pattern.

In a publication purported to quantify the work done by muscles in running, Elftman (1940) identified energy savings in the recruitment of two-joint muscles. In a treatise on the biomechanics of muscle, Elftman (1966) underlined that two-joint muscles can transfer at the hip joint the energy received at the knee; with one-joint muscles this energy would be wasted. In Elftman's view, the fine tuning of the motion would be assumed by the one-joint muscles.

Looking at the muscle function in locomotion, Morrison (1970) also brought out evidence of energy savings associated with the use of the biarticular muscles acting on the knee. His study consisted of the application of inverse dynamics methods to analyze of the data from six experiments in which subjects walked under different conditions: level at different speeds, up and down stairs, up and down a ramp. He pointed out that the energy savings could be chemical rather than mechanical. Morrison furthermore linked the presence of two-joint muscles to a saving in muscle bulk.

Wells (1988) developed a decision algorithm to partition the joint moments of force (at the hip, knee and ankle) between the one and two-joint muscles. For walking, Wells estimated that the transfer of energy by two-joint muscles reduces the mechanical energy cost by 7 to 29% during fast walking (with an average of 11.6% for walking at different speeds) when compared to single-joint muscle recruitment alone.

With the use of an EMG driven muscle model, Yack, Winter and Wells (1988) examined the economy of two-joint muscles during gait. It was determined that the moments of force generated by the biarticular muscles of the leg during both walking and jogging took place but persisted outside the time period that required the occurrence of the necessary moments; this substantiates the possibility of paradoxical activity from the biarticular muscles. The average power transferred represented 18%, 15% and 12% of the total muscle power for m. rectus femoris, the hamstrings (medial and lateral) and m. gastrocnemius respectively. Their estimation of the possible energy savings was based on prediction of the power transferred by two-joint muscles and ranged from 8% to 22% for the muscles studied. Those savings were attributed to transfers of energy between segments through these muscles. It was also found that more power was transferred by m. gastrocnemius at faster locomotion speeds (jogging: 22%) than during slow walking (8%). Another important characteristic of biarticular muscles that has been pointed out by Winter (1990) is their ability to transfer energy during isometric contractions.

It is, therefore, generally admitted that one of the functions of biarticular muscles is to reduce the energy cost of movements. On the other hand, as mentioned by Gregor, Cavanagh and Lafortune (1985), the use of two-joint muscles can lead to a decreased efficiency: During Lombard's paradox, the additional energy expenditure results from the antagonist action of the muscles. The two biarticular muscles work against each other at each joint and each joint movement is determined by the contraction of the muscle on the side with the greatest mechanical advantage (which still has to overcome the activity of the antagonist side).

Gregor, Cavanagh and Lafortune (1985) presented an integrated description of ergometer cycling. With five recreational cyclists as subjects, the investigators used kinetic, kinematic and EMG measurements to describe the function of the lower limb. The force applied to the pedals was measured in the sagittal plane with a strain gauge force transducer. It was found that, during the propulsive phase, the joint moment at the knee shifted from extensor to flexor while the moment at the hip remained extensor. The authors stated that the clear difference in knee and hip action constitutes a creative solution to Lombard's paradox. The paper also relates the mean joint torques to the EMG activity (based on elite cyclists data from Gregor, Green and Garhammer, 1982) and describes how the knowledge of both parameters can help in the analysis of a given motion (although no electro-mechanical delay had been taken into consideration).

The principle of energy transfer through tendinous action lies in the nature of biarticular muscles. Transfer can not take place within slack bands; therefore, either the muscle has to be minimally contracted or its inherent passive tightness can allow for the transfer. Rasch and Burke (1978) remarked that the hamstring muscles are usually tight enough to transfer energy through this mechanism while most other muscles are not. As reported by Elftman (1966), in most cases the fibre length in two-joint muscles is not sufficient to permit cumulative movement in both articulations. More to the point, Elftman suggested that the arrangement of two-joint muscles allows them to be stretched by the events taking place at one joint while being shortened at the other. Winter (1990) postulated that the fibres of many of the biarticular muscles of the lower extremity could be too short to allow complete movement at both joints. All these hypotheses contrast with the work of Markee *et al.* (1955). These investigators had highlighted that the fascial attachments of the semitendinosus, rectus femoris and sartorius muscles, apart from allowing independent actions at the hip and knee, act through their full range of motion irrespective of the position of the other joint. From the results of the morphological part of their study, Markee *et al.* generalised that "only those fibres which do not pull on the fascia are incapable of moving the hip when the knee is in certain positions".

In a study of explosive jumping, Grégoire, Veeger, Huijing and van Ingen Schenau (1984) attempted to shed more light on the asynchronous occurrences of the power peaks at the hip, ankle and knee joints obtained by Vergroesen, De Boer and van Ingen Schenau (1982) in a similar investigation. The authors combined the measures of joint angles, angular velocities, net moments of forces and ground reaction forces with EMG signals from eight leg muscles to examine 24 countermovement jumps from eight subjects. An energy flow was found to take place in the proximodistal direction. The principle of power transfer was used to explain the high moments of force observed at the ankle joints; these torques would not be possible without transfer since the angular velocity of the ankles reached over 1000 deg/s. The authors also stated that the rectus femoris and gastrocnemius muscles can deliver higher forces than their single-joint counterpart due to their relatively lower contraction velocity. It could then be speculated, from a pure physiological point of view, that the energy cost to be associated with this slower contraction rate is lower. This possibility may arise under two specific conditions: in repetitive movements involving slow-twitch fibres or if a lower number of fast-twitch motor units are recruited.

In the view of Grégoire *et al.* (1984), the use of two-joint muscles in jumping allows for direct conversion of segmental rotational energy to the translation of the centre of gravity of the body, hence avoiding the need for segment deceleration through costly mono-articular eccentric contractions. Van Ingen Schenau, Bobbert and Rozendal (1987) also examined two-legged vertical jumping, with an experimental protocol similar to that of Grégoire *et al.* The results, obtained from ten experienced jumpers, substantiated the idea that biarticular muscles have a unique function in the transformation of rotations in joints to translations of the body. Proximodistal energy transport would take place through the gastrocnemius muscle. This way, work generated by the knee extensors could be transferred to the ankle and used for plantar flexion.

With measures of ground reaction forces, EMG activity and with cinematographic records, Bobbert and van Ingen Schenau (1988) tested ten skilled subjects also performing countermovement jumps. The results confer an optimizing role in energy use and sequencing to the biarticular muscles of the lower extremity. An interesting aspect discussed by the authors is the contribution of the biarticular muscles to limit joint extension, hence protecting from hypertension with a lower expenditure in energy than would be required by the monoarticular muscles.

Pandy and Zajac (1991) presented the application of an optimal control solution [four-segment/eight muscle dynamical model developed by Pandy, Zajac, Sim and Levine (1990)] which results were compared to the results of inverse dynamics applied to five adult males during jumping. The subjects performed three hands-on-hips vertical jumps aiming for maximum height. The dynamic model was intended to compute optimal controls, body-segmental motions, muscle forces and muscle activations for maximum height. From the results, Pandy and Zajac refuted the notion that jumping performance was enhanced by the unique biarticular action of m. gastrocnemius.

Van Leeuwen and Spoor (1992) discredited part of these conclusions in pinpointing a lack of accuracy in the muscle moment arms and the use of an exaggerated stress-strain relationship for the tendons. Van Leeuwen and Spoor agree to the likelihood that a combination of mono- and biarticular muscles have higher energy output than in a leg with mono-articular muscles only (for equal muscle mass), but underline the need to test that the energetic advantages outweigh the energy losses in biarticular muscles. Van Soest, Schwab, Bobbert and van Ingen Schenau (1993) created a computer model to simulate the action of m. gastrocnemius in human jumping. The model allowed to compare the effect of a hypothetical monoarticular gastrocnemius muscle with its biarticular counterpart. With the biarticular design, the jumping height was slightly superior (by 1 cm)—these results contrast with the findings of Pandy and Zajac (1991). The study also shows that slight differences in modelling can have important effects on the final result. The authors pointed out the need to account for anatomical constraints with precision (moment-arm—knee angle relationship).

Simonsen, Thomsen and Klausen (1985) examined the activity of mono- and biarticular leg muscles in sprint running. Paradoxical action was found to be the probable explanation of activity from m. gastrocnemius and the hamstring group during the extension of the knee at the end of the push-off. Interestingly, these investigators measured greater variations and rates of variation in muscle length in biarticular than in single-joint muscles. This is contradictory with the observation of a lower contraction velocity in two-joint muscles during jumping made by Grégoire *et al.* (1984). A recent study by Prilutsky and Zatsiorsky (1994) associates the tendinous action of two-joint muscles with energy transfers between joints. Eight muscles were looked at and the difference between the power from the net moments of force and the power from the muscle was estimated in running and jumping from five subjects. It was found that, during the push, energy transfer took place towards the distal end of the segment *via* the biarticular rectus femoris and gastrocnemius muscles. During landing energy was transferred from distal to proximal joints to be absorbed at the hip by the monoarticular muscles.

Through a neurophysiological approach, Hogan (1985) provided insights into the possible function of some neuro-musculo-skeletal structures with a study of multi-joint posture and movement control. The investigator showed how some considerations from single degree of freedom systems may be generalized to multiple degree of freedom systems. After a spring-like description of muscle force versus length, concepts of mechanical impedance and admittance are proposed to describe the dynamic aspect of postural behavior (mechanical impedance refers to the neuromuscular system and describes an organization which accepts motion inputs and yields force outputs while the concept of mechanical admittance, here, portrays the skeleton which, from force inputs, yields motion outputs). In the model, the ability of the central nervous system to modulate the mechanical admittance (inertial behavior) of the skeleton complements the ability to modulate the mechanical impedance of the neuromuscular system (viscosity, stiffness, etc.). The central nervous system "may modulate its inertial behavior by repositioning the limb". In Hogan's view, the presence of multi-joint muscles dramatically increases the extent to which the velocity-dependant component of postural behavior may be controlled by the coordination of muscle activity. In a paper on the control of multijoint motor behavior, Hogan, Bizzi, Mussa-Ivaldi and Flash (1987) concluded that polyarticular muscles contribute to the mechanical impedance in a unique way in that they would serve to distribute joint moments and powers. They also advanced that redundancies, although invariably perceived as a complicating problem in the description of motion, may themselves be a solution to the problem.

Overall, much speculation exists with regard to the role of biarticular muscles. Joint motion has been described as a function of the mechanical advantage based on the length of each muscle's lever arms (Lombard's paradox). Taut biarticular muscles can also act like belts, which action has been described as tendinous (Cleland, 1867; Lombard, 1903a; Elftman, 1939; Rasch and Burke, 1978). Economy of mechanical and metabolic energy (Elftman, 1940, 1966; Morrison, 1970; Wells, 1988; Yack, Winter and Wells, 1988) and savings in muscle bulk (Morrison, 1970) have been associated with biarticular muscles. In addition, higher energy expenditure has been seen as a possible fallout of their recruitment during Lombard's paradox (Gregor, Cavanagh and Lafortune, 1985). Some authors advanced the possibility that both ends of a biarticular muscle contract independently, therefore acting as two distinct mono-articular muscles (Markee *et al.*, 1955). There is ample evidence in support of the idea that mechanical energy and power can be transferred between segments through biarticular muscles (Elftman, 1966; Grégoire, Veeger, Huijing and van Ingen Schenau, 1984; Rozendal, van Ingen Schenau, Bobbert and van der Woude, 1986; van Ingen Schenau, 1989; van Ingen Schenau, Bobbert and Rozendal, 1987; Winter, 1990; Prilutsky and Zatsiorsky 1994). The control of limb mechanical impedance by multi-joint muscles has also been advanced (Hogan, 1985; Hogan, Bizzi, Mussa-Ivaldi and Flash, 1987). It transpires from the literature that the role of two-joint muscles is not yet unanimously defined.

Classification schemes

Attempting to describe the functional roles of the leg's two-joint muscles, Molbech (1965) revisited the concept of Lombard's paradox and narrowed down its study to within a closed muscular chain. Taking into account the instantaneous position of the centre of rotation of the joints, he analyzed mathematically (from geometrical considerations) the paradoxical effect of biarticular muscles passing the knee joint in a movement where one end of the chain is steered and the other fixed. Ranges of angles were found for which the m. gastrocnemius and m. biceps femoris can have either a flexing, extending or purely stabilizing effect on the knee joint.

Carlsoo and Molbech (1966) sought to validate Molbech's findings (1965) with raw EMG measurements from dynamic movements. Two types of motion were compared: upright standing with knee flexion and extension (in open and closed chains) and cycling. For the knee bending action different muscle behaviours were identified depending upon either fixation or free hanging of the lower extremity (foot). The results from cycling support the notion that, during one cycling revolution, the effect of a muscle contraction can shift from flexing to extending the joint; this, according to the authors, becomes paradoxical with the muscle function studied in a freely hanging extremity.

Molbech's approach to the determination of the functional role of biarticular muscles has been criticized by Andrews and Hay (1983). These authors identified limitations in the closed-system analysis. They also pointed out the absence of a pre-determined reference frame that would be needed to locate the instantaneous centre of rotation of any body segment.

Stanhope (1982) also attempted to verify the applicability of Molbech's (1965) mathematical model. With the use of integrated EMG from rectus femoris, vastus lateralis and biceps femoris muscles plus knee angle measurements, unloaded squat-to-stand motions were examined. The results do not warrant confirmation that Molbech's model describes the movement. Stanhope's recommendations for further studies include the addition of kinetic measurements and the assessment of the same movement with a load.

A dynamic solution to the determination of the functional role of two-joint muscles has been proposed by Andrews (1982). Based on Lagrangian equations of motion, an algorithm was designed to predict the orientation of the 2D-one degree of freedom link system from predetermined initial conditions. The velocity subsequent to a release from rest was used to establish the functional role of the hamstring. Like Molbech's classification scheme, the method allowed for changes in the muscle function throughout the range of motion. However, this modelling method ignored the techniques of equilibrium analysis.

Andrews and Hay (1983) redefined modelling requirements regarding joint, muscle and axis of rotation of the joint. The Molbech-Carlsoo classification method for the determination of the functional role of the muscle was analyzed and compared to the classical method—the classical method being based on joint configuration.

Andrews (1985) elaborated a general classification method from equilibrium analysis techniques. The procedure is grounded on the premise that the initial configuration of the system will be departed from as the length of the muscle is decreased. This classification method, known as the Andrews-Kinematic (A-K) does not depend upon the type of muscle contraction (eccentric, concentric) nor on the action of other muscles. For comparison purposes, Andrews (1987) applied the A-K method in parallel with the Standard-Kinetic (S-K) method to describe the functional role of muscles from the data of Gregor's, Cavanagh's and Lafortune's (1985) experiment (Gregor *et al.* had used EMG with joint moments to examine the functional role of hamstrings and quadriceps muscles during cycling). As both methods provided different results in the detection of paradoxical behavior, the two showed the presence of paradoxical behavior to different extents.

From the results of an experiment on isometric contractions and walking, Wells and Evans (1987) concluded that "two-joint muscles are preferentially recruited if the task demands joint moments such that the two-joint muscles can contribute to both simultaneously". In another investigation, Wells (1988) makes use of the same deterministic approach (for which the criterion is not optimality). This algorithm has been criticised by van Ingen Schenau (1989) who points out that the activation of biarticular muscles is not dependant on the net moments: They would rather, with the monoarticular muscles, determine these moments.

Wilson (1988) used inverse dynamics to examine the lower limb muscle function during deep-knee bending. His subjects, all skilled weight lifters, performed a full squatting motion with no load and with a load corresponding to approximately 80% of their maximum. The study showed that, for this type of motion, two-joint muscles are used to stabilize the joints (namely hip and knee) and that the prime movers during the ascending phase of the squatting motion remain the mono-articular muscles of the leg. For a more constrained movement, bicycling an ergometer, Curry (1989) came to the same conclusions in that the prime movers of the cycling motion are the one-joint muscles of the lower limb and that the role of the biarticular knee flexors was to stabilize the joint(s). These results were supported by an electromyographical field study of cycling conducted by Clarys, Cabri and Gregor (1988) who concluded that the absence of muscular paradox may be supported.

With the publication of responses to a target article from van Ingen Schenau (1989), a whole issue of Human Movement Science has been devoted to the subject of ***multi-joint movement and the unique action of biarticular muscles***. The purpose of the article was to identify the constraints pertaining to the transformation of joint rotations into translation of the segments and of the centre of gravity of the whole body. From cycling, jumping and speed skating data, van Ingen Schenau examined the sequential recruitment of the leg muscles and the cocontraction of the knee extensors with their biarticular antagonists. The author explored the relation between rotation and translation evoked by Grégoire *et al.* (1984) and van Ingen Schenau *et al.* (1987).

The four constraints identified were: a geometrical constraint describing the transfer of rotation to desired translation velocity, anatomically based requirements for the deceleration of angular velocity in joints prior to full extension, the distribution of net moments in joints to exert external force in the desired direction and the orientation of the external force. In conclusion, van Ingen Schenau emphasised the need for top-down studies. As pointed out, the constraints aforementioned could not have been identified without an analysis in relation to the external forces (ground or pedal reaction forces and gravity with the mechanical goal of the movement).

As Andrews (1987) remarked, the detection of paradoxical behavior is dependent on the method chosen to determine the functional role of the muscle. To best assess this role, several authors (Carrière and Beuter, 1990; Gregor, Cavanagh and Lafortune, 1985; Martindale and Robertson, 1984; Stanhope, 1982; Wilson, Robertson and Stothart, 1988) have recommended the use of an integrated approach that would include EMG, kinematic and kinetic measurements.

Rowing

Nelson and Widule (1983) completed a kinematic analysis of rowing on a Stanford ergometer. Eighteen intercollegiate female rowers were filmed during the drive phase of the stroke. In the quantification of the kinetic energy of the segments, the contribution of the translational kinetic energy was omitted supposedly due to the nature of the rowing motion. Thus, it was simplistically concluded that translational kinetic energy did not provide a significant contribution to the understanding of rowing. From the sum of the possible angular velocity of the trunk and knee, the authors also calculated a lower efficiency in the novice rower when compared to the more experienced.

Through the use of cinematography and link-segment mechanics, Martindale and Robertson (1984) compared the energy savings due to exchange and interconversion of segmental energy for both single skull and ergometer (Gjessing) rowing. The rowing of the ergometer was examined under two conditions: with the machine fixed and with the machine free to move, being supported by wheels. Contrary to Nelson and Widule's (1983), their assessment of the mechanical energy took the translational component of the segmental kinetic energy into account. It was found that the energy savings through exchange were greater on the water due to exchange of energy between the boat and the rower. The results also reveal that less internal work was performed on the wheeled ergometer than on the water. In their recommendations, the need for complete power analysis of the rowing stroke to determine the work done by the various muscle groups was underlined.

A vector loop model has been developed by Lamb (1989) to determine the correct sequence of action during the drive phase of sweep rowing. With this instrument, the author compared the kinematics of on-water and ergometer (Stanford) rowing. The results of the comparison support the hypothesis that ergometer rowing simulates rowing. Furthermore, the author saw the use of kinematic measures from ergometer rowing as a supplement to the physiological measurements used for selecting rowers.

Wilson, Robertson and Stothart (1988) investigated the electromyographical activity of the main muscles of the lower limb and the force applied to the handle in rowing a Gjessing ergometer. Nine University level male athletes rowed the machine. The results give credence to Lombard's paradox as a possible explanation of the conspicuous antagonistic activity of the knee extensors and flexors. As the authors point out, a more complete assessment is needed to confirm or rule out the occurrence of paradoxical recruitment.

Rodriguez, Rodriguez, Cook and Sandborn (1990) also undertook an electromyographic analysis of the rowing stroke performed on an ergometer (Concept II). The stroke was divided in six phases being the beginning, mid- and end of drive and the beginning, mid- and end of recovery. The activity of the main muscles of the upper extremities, torso and lower extremities was examined. In spite of an absence of comments in this direction, it can be observed directly from the results (graph) that maximum EMG from the hamstring group occurs simultaneously (during the mid-drive phase) with the maximum from the calf, vastus lateralis and vastus medialis muscles. The examination of the recovery is self-limiting because, on the Concept II (as it is on the Gjessing), no resistance is present at the handle during this phase. All-in-all, Rodriguez *et al.* (1990) questioned the suggestion made by others that power training of specific body segments is more useful to competitive oarsmen than overall strength training. The authors emphasized that the combined activity of two or more groups of muscles is of more importance to performance than the strength of an individual muscle.

In a thorough review on the mechanics of rowing, Zatsiorsky and Yakunin (1991) recognized the scarcity of information pertaining to the forces applied to the rower's body. This can, in part, be explained by the technical impediments associated with the measure of these forces. Few attempts have been made to quantify the reaction force on the rower's feet. In 1969, Kirsanov (cited in Zatsiorsky and Yakunin, 1991) made comparative measurements of the forces applied to both sides of the foot stretcher with strain gauges during rowing. The results showed that the inside leg thrust preceded the outer leg whereas the outside leg exerted a greater force. For sculling, Zhigalov and Morzhevikov (cited in Zatsiorsky and Yakunin, 1991) found both forces to be approximately identical. To date, no accurate measurement of the forces with their direction of application has been reported.

Conclusion

To date and until the force developed within each muscle can be measured directly, indirect methods (inverse dynamics in parallel with EMG measurements) seem the most practical alternative for predicting muscle force and identifying muscular function. Although the rowing motion has been examined extensively, there is a clear lack on the quantification of the forces applied to the rower. Even though research has made some general steps in the understanding of the role of two-joint muscles, their exact function remains uncertain. Offering an opportunity to limit the study to a well constrained and controlled motion, ergometer rowing might be the tool to determine whether the biarticular muscles of the leg act in a paradoxical fashion.

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