LOWER LIMB MUSCLE LENGTHS IN ROWING: A PRELIMINARY STUDY

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This study aimed to characterise the lower limb muscular coordination in rowing. A musculoskeletal model was developed to be used for movements exhibiting large joints range of motion. Maximum static muscle lengths computed from five static stretching tests were compared with muscle lengths extracted while rowing. Muscle lengths were derived from lower limb kinematics collected using a motion analysis system. Our results showed that classical stretching tests were suitable for a muscle group but must be more specific to target isolated muscle. During rowing trials, bi-articular muscle patterns were subject-dependant with hamstring lengths close to their maximum lengths. Asymmetries were observed for few muscles. Further studies are necessary to confirm these promising findings that may maximise rowing performance and minimise rowing injuries.

KEY WORDS: musculoskeletal model, elasticity, stretching, ergometer.

INTRODUCTION: Performance in rowing is determined by the time to cover 2000 m, and therefore to maintain a large external power during each of the 200 to 250 rowing cycles performed during this race distance. Although each rowing cycle involves all the body segments and approximately 70% of the body's muscle mass through a complex muscular coordination, recent studies have shown than more than 50% of the external power is generated by the lower limbs (e.g. Kleshnev, 2016). The rowing cycle lead to large force generation at the feet and full range of motion for each lower limb joint.
A way to maximise rowing performance and minimise rowing injuries would be to develop subject-specific set-up and equipment, i.e. stretcher, oar, blade, rigger. Until now, innovations in rowing are based on a trial and error process and with a view on only one (maximising performance) or the other (minimising injuries) part of the rowing activity. However, the musculoskeletal system is a complex system including muscle redundancy and joint coupling via the bi-articular muscles. Any changes of set-up or equipment may have unexpected consequences on the dynamics of the rowing cycle. As a result, these changes should be developed and evaluated using a musculoskeletal modelling approach to better anticipate their whole consequences on muscular coordination in rowing.
The muscle length variation is a first approach to assess muscular coordination during dynamic movement (Deliu & Ibrahimaj, 2015). The maximal muscle length obtained during static stretching tests may be used to individualise the reference muscle elasticity. However, classical static stretching tests lack validity and reliability because joint angles are estimated using metric tools such as ruler or goniometer (e.g. Ayala et al., 2011). In this context, musculoskeletal modelling should also be a more accurate approach to investigate muscle length during static stretching tests. However, the ranges of motion of the main lower limb musculoskeletal models are limited to gait analysis and therefore do not cover the ranges of motion reached during both static stretching tests and rowing.
This study aimed to investigate muscle length and asymmetry during rowing. For that purpose, a musculoskeletal model of the lower limb was developed for movements exhibiting full joints range of motion.

METHODS: The joint limits of the lower limb musculoskeletal model developed by Arnold et al. (2010) (12 segments, 24 degrees of freedom, 44 muscles) were increased according to the values reported in the literature for rowing (Buckeridge et al., 2012) and static stretching tests (Kapandji & Judet, 2009). Geometric modifications of this generic model were necessary for 29 muscles to avoid collisions with bones. The effects of these modifications were carefully checked and adjusted with respect to the muscular characteristics described in the literature (e.g. Delp et al., 1999; Bufford et al., 1997) in particular at the joint limits.
Two male rowers (age: 18/24 years; mass: 83/70 kg; height: 1.78/1.74 m) competing at a national level gave their informed consent to participate in this study. Sixty-six reflective

markers were placed on 15 body segments: pelvis (8), thorax (5), head (3), thighs (6×2), shanks (6×2), feet (6×2), upper arms (3×2), forearms (3×2) and hands (3×2). Additional markers were placed on the rowing ergometer (6) and on the devices specifically build for the sit and reach test (2), and plantar flexor test (4). The marker three-dimensional trajectories were recorded using a 20-camera motion analysis system sampling at 100 Hz (T40, Vicon, Oxford, UK). The participants performed setup movements for functional locating all the joint centres using the SCoRE algorithm (Ehrig et al., 2006). Then a trial with the participant in a static anatomical position was recorded to scale the Opensim generic model to the subject's anthropometry (Delp et al., 2007).

After a routine warm-up, participants were tested for 30 seconds at 20 cycles / minute, 32 cycles / minute and race pace on a Concept2 Dynamic Indoor Rower (Concept2, USA). Ten consecutive cycles were selected in the middle of each trial. The catch and finish events of the ten cycles were automatically detected to time-normalised [0, 100%] and time-averaged for the 10 cycles the length of 15 muscles. The muscle length was normalised with the maximal muscle length (Lstat) computed by Opensim 3.2 routines from five static stretching tests performed by participants (Figure 1): Modified Thomas Test, Passive Leg Straight Raise Test (PSLR), Sit and Reach Test, Plantar Flexor Test and Crouched position.

Figure 1: Illustration of the five static stretching tests used in this study to extract the maximal muscle length (Lstat). A: Modified Thomas test. B: Passive Leg Straight Raise Test (PSLR). C: Sit and Reach Test. D: Plantar Flexor Test. E: Crouched position.

RESULTS: Although the Sit and Reach Test is a symmetrical task, Lstat showed an asymmetry of about 0.7 cm between right and left erector spinae for each participant. Lstat of four muscles can be computed by two different static stretching tests (Table 1). The differences observed between the two tests were small, between 0.4% for the biceps femoris short head (participant 2) and 8.2% for the gastrocnemius lateralis (participant 2). The larger value of Lstat for some muscles was always reached for the same test.

Table 1: Maximal static length for four muscles on right side for each subject.

Muscle	Test	Length (cm)	
		Participant 1	Participant 2
Biceps femoris short head	**Sit and reach test**	**23,7**	22,4
	Passive Leg Straight Raise test	23,6	**22,6**
Semitendinosus	Sit and reach test	51,5	51,2
	Passive Leg Straight Raise test	**53,4**	**52,1**
Soleus	Plantar Flexor test	35,2	38,4
	Crouched Position	**35,7**	**39,3**
Gastrocnemius lateralis	**Plantar flexor test**	**48,7**	**52,8**
	Crouched position	44,7	49,2

Comparison of muscle length profiles between cycle rates revealed similar patterns for all muscles. Generally the curves at the highest rate were slightly shifted to the right during the propulsion phase. During the rowing cycle, the mono-articular muscles showed mostly large length variations: erector spinae (2.8±0.4 cm), gluteus maximus (3.1±0.6 cm), gluteus medius (0.9±0.3 cm), vastus lateralis (6.2±0.7 cm), vastus intermedialis (6.3±0.6 cm), vastus medialis (6.1±0.6 cm), biceps femoris short head (7.2±0.5 cm) and soleus (3.7±0.1 cm). Their patterns were very basic (elongation and shortening during the propulsion and recovery phases, respectively; shortening and elongation for the biceps femoris short head) and similar to the pattern of the corresponding flexion/extension degree of freedom. The only exceptions were erector spinae and gluteus medius that showed a more complex pattern. The length variations of the bi-articular muscles were mostly smaller than the mono-articular muscles: rectus femoris (1.7±0.8 cm), biceps femoris long head (2.1±0.5 cm), semitendinosus (3.0±0.6 cm) semimembranosus (2.8±0.5 cm), gastrocnemius medialis (1.1±0.7 cm), gastrocnemius lateralis (1.0±0.5 cm), at the exception of the tensor fascia lata (9.2±1.5 cm). Their patterns were subject-dependant. Hamstrings exhibited a relative maximal length very closed to Lstat (Figure 2). For the erector spinae, the maximal lengths were 2% larger than Lstat for participant 2.

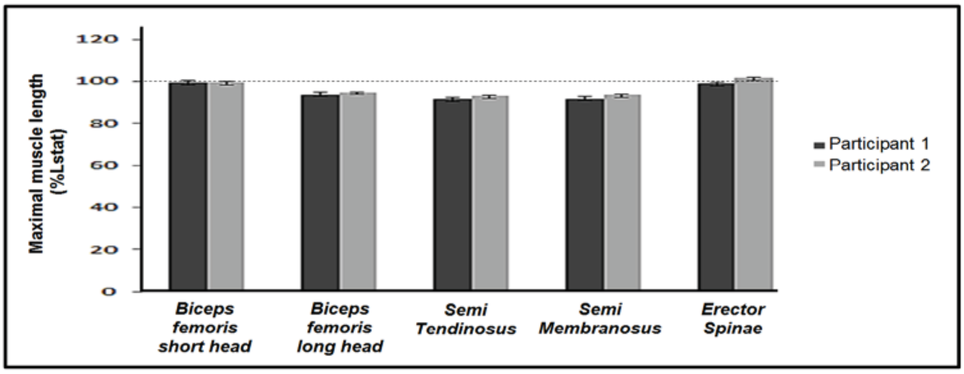

Figure 2: Relative maximal lengths for hamstrings and erector spinae (right side) on the rowing ergometer at 20 cycles / minute (mean and standard deviation).

Asymmetric patterns were observed for rectus femoris, gastrocnemius medialis and lateralis and soleus. The maximal differences between the two gastrocnemius lateralis were about 20 mm and 10 mm for participant 1 and 2, respectively (Figure 3).

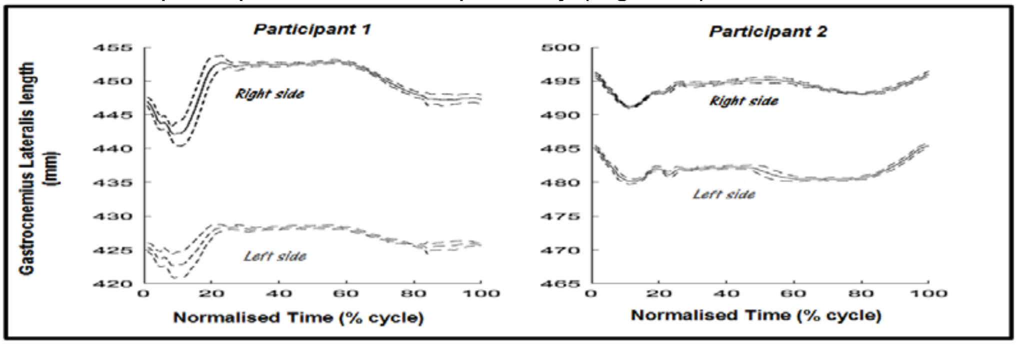

Figure 3: Absolute lengths for right and left gastrocnemius lateralis on the rowing ergometer at 20 cycles / minute (mean and standard deviation).

DISCUSSION: Our results highlighted that the lower limb static stretching tests published in the literature are specific to mono-articular or bi-articular muscles although they are generally used to assess the global elasticity of muscles including both mono and bi-articular muscles (e.g. triceps surae, Halperin et al., 2014). For example, our results clearly showed that the maximal length of the soleus is reached only if the two gastrocnemii are relaxed. In other words, estimating the maximal static muscle length of a muscle must be clearly associated with a specific joint configuration. Musculoskeletal model is a reliable tool to identify the best joint configurations that lead to the larger muscle length. Further studies must be undertaken to support this finding. The specificity of static stretching test should be analysed in details to furnish clear recommendations on which test to use to estimate the elasticity of a target muscle. This point is particularly crucial when the maximal muscle length must be estimated as in this study.

During ergometer rowing trials, length of mono and bi-articular muscles evolved differently. Mono-articular muscles showed an important length variation throughout the rowing cycle while the bi-articular muscles were associated with a low variation profile, close to an isometric contraction or sometimes an eccentric contraction. Moreover, hamstrings reached their maximal muscle length computed from the static stretching tests. This maximal muscle length was exceeded for erector spinae. Two hypotheses can be put forward to explain these results. The first hypothesis is that the static test chosen to estimate the maximal muscle

length was not as specific as expected for the target muscle. As an example, the static test used in our study to estimate the maximal length of the erector spinae was likely limited by the hip flexors. The second hypothesis is the muscle length reached during a dynamic movement is more important than the static maximal muscle length as a consequence of the inertia of the segments. The mass of the head and trunk is approximately 60% of the total body mass. Even if the accelerations of the body segments are low in rowing, their momentum may have a large impact at the catch, when the global movement of the rower is reverse. These high values observed for the posterior muscular chain may place tissue structures at risk of injury.
Four muscles showed asymmetric patterns for their length variation throughout the rowing cycle. A part of these asymmetries may be explained by the difference in length between the two lower limbs (1.8 and 0.8 cm for participants 1 and 2 respectively). However, as three of these four muscles were bi-articulars, another part may be explained by low joint kinematic asymmetries amplified by a low desynchronisation between the two joints crossed by these muscles.

CONCLUSION: Lower limb muscular coordination was investigated in national rowers when rowing on a mobile ergometer at training and race paces. The results showed that static tests used to estimate the maximal muscle length must evolve in order to be more specific to the target muscle. They highlighted specific kinematic for the mono and bi-articular muscles and the muscles of the lower limb posterior muscular chain. Further studies should be realised to confirm these promising findings and provide useful information to coaches and rowers for maximising rowing performance and minimising rowing injuries.

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