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DYNAMIC ANALYSIS OF ROWING ON CONCEPT II TYPE C ERGOMETER

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ABSTRACT: The purposes of this study were to: a) determine the potential of rowers' strength and the degree of its utilization during rowing, b) provide a quantitative description of the rowing technique. The crews of two quadruple sculls took part in the study. First, the torque of the main muscle groups was measured in statics. Then, participants performed 3 series of strokes at rates: 32, 36 and 40 c/min. Subsequently, the inverse dynamics problem was solved. Torso as well as hip extensors are the strongest muscle groups of rower. The hip extensors indicated the highest degree of utilization. It seems that rowing results could be particularly improved by increasing the strength of the hip extensors. Using the muscle torques, generated by large muscle groups during rowing, as guiding parameters will allow for an optimal selection of a high class crew.

KEY WORDS: rowing, strength utilization, sport technique, inverse dynamics problem, joint moment

INTRODUCTION

The time score achieved by a rowing crew during a race will depend on the average boat speed and the length of the distance covered. The average boat speed is a function of many parameters, in particular:

a) Force applied by the rower [F(t)] to the oar,

b) Duration of the pull, during which the rower applies force to an oar immersed in water,

c) Duration of the recovery phase, during which the rower shifts the oar back over the water in order to start another drive phase [43]. One full cycle is composed of the sum of the drive phase and recovery phase durations. The stroke rate increases as a result of reducing the recovery phase duration with the drive phase duration remaining unchanged [37,42], or as a result of reducing the duration of both the phases [39]. According to Schneider et al. [42], the maximum force applied to the oar does not change when the stroke rate increases, but Pudlo et al. [39] believe that it does grow. Nevertheless, it is not the maximum force applied to the oar that determines the boat speed, but the average force [44], which grows along with the stroke rate [9]. Each rower has his own F(t) pattern (measured on the oar) and oar grip trajectory that are independent from the stroke rate. Rowers of a good crew display similar characteristics [3,9,17,42]. The force that a rower exerts on the oar is a resultant of internal forces (muscles) and external forces (gravity, inertia, resistance to motion). An in vivo measurement of the force developed by a muscle is connected with the necessity to insert a tensometric transducer in the tendon [12,29]. This invasive procedure is rarely performed in sport practice. Moreover, a movement is effected by a group of muscles and not a single one, so the muscle torque [M(t)] of selected muscle groups is measured [6,11].

Janiak et al. [21] measured the muscle torque of main muscle groups in rowers in statics and found that the strongest muscles were hip flexors (714 Nm) and torso flexors (697 Nm). Kopański and Krzywania [30] studied the isometric rowing strength on the handle in six drive stages, and its value was in the range of 1050-1650 N Secher [44] compared his own isometric rowing strength research results with those of Ishiko [16], who studied the force applied to the oar during rowing in a boat and found that the dynamic rowing strength accounted for 39% of the isometric rowing strength.

Dworak [10] compared the results obtained by Łazareva et al. [34] concerning the average value of the force applied to the oar during a 2 km race with the results of Kabsch et al. [26], who studied the maximum isometric strength on the oar in the catch position (1440 N). He found that the force applied to the oar during a 2 km race accounts for 16% of the maximum isometric strength on the oar in the same position of the oar.

Since it is practically impossible to measure the muscle torque during a movement once solution is to use the modeling method. Use of this method allows us to estimate muscle torque. In sports biomechanics, modeling is used to solve the inverse dynamic problem, which consists in taking into account empirical kinematic data, external force measurement results, as well as mass and geometric parameters of the body segments, when calculating muscle torque. As a result you end up with an answer to the question: How did the central nervous system control a specific movement (what was the movement's technique?) [7,27,31].

Although the literature concerned with this subject most frequently contains images of the rowing technique in the form of verbal descriptions or drawings of subsequent motor acts [1,8,28] it is seldom supported by any numerical values [8]. Therefore it excludes the possibility to perform a quantitative and unambiguous identification of the sport technique. Meanwhile, according to Kornecki and Lenart [32], the sport technique is one of the possible realizations of a sequence of elementary motor acts performed as a result of the central nervous system controlling the interaction between muscle forces and external forces. With this coordination one can seek to successfully realize a movement with an optimal utilization of the physical and mental characteristics of the person. In practice, the quantities used to identify the technique are the time courses of the torque of the muscles which actuate the sportsman's large joints, with the help of which the central nervous system controls the person's movements.

Hence, the purpose of this study is to determine the potential of the rowers' strength and the degree of its utilization during rowing on the Concept II type C ergometer at different stroke rates, as well as to provide a quantitative description of the rowing technique different skills competitors. Such a description will allow for a better understanding and identification of the specific components of rowing biomechanics, a modification of which will improve sport results.

MATERIALS AND METHODS

Rowers of two quadruple sculls were tested in this study. The first crew (high class) was 22.8±1.5 years old, with body height 1.91±0.01 m and body mass 90.0±2.2 kg. The second crew (intermediate class) was 19.6±0.8 years old, with 1.91±0.06 m and 82±8.1 kg, respectively. Prior to participation, subjects provided informed consent in accordance with the institutional review board. Subsequently, points were marked on their bodies that corresponded to transversal axes of their joints: wrist joint, elbow joint, shoulder joint, hip joint, knee joint, ankle joint and V metatarsophalangeal joint, and anthropometric measurements were taken. Then, the torque

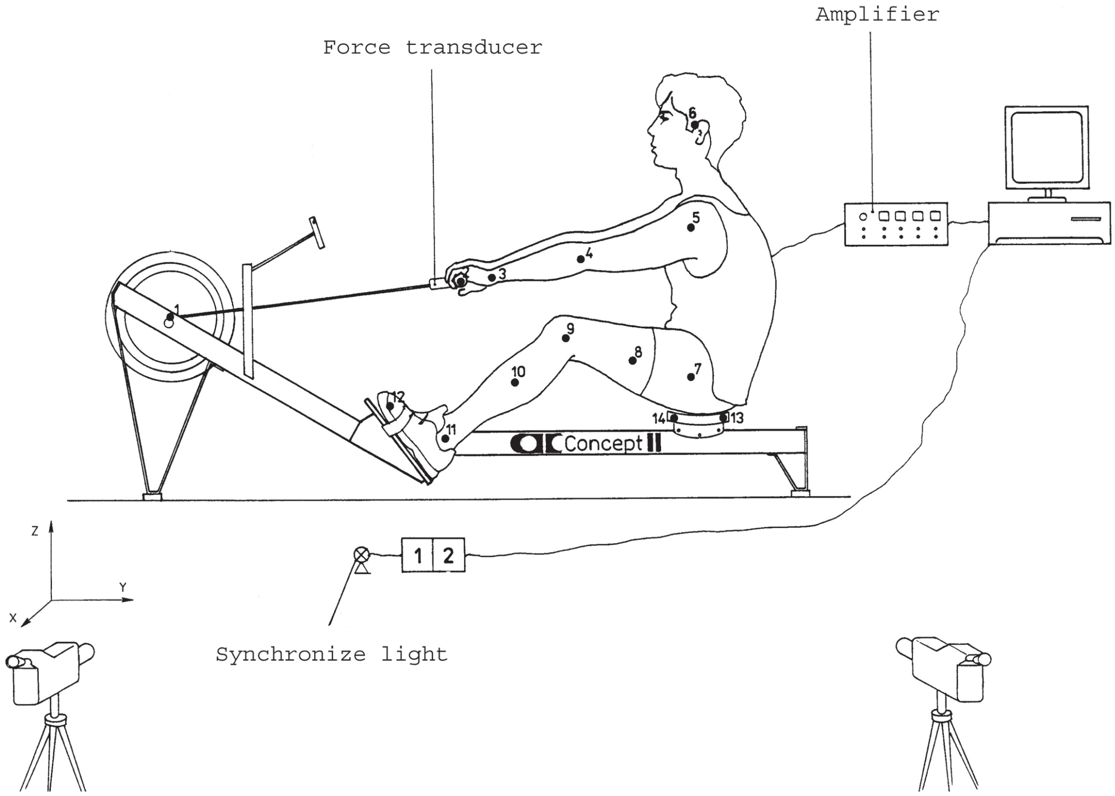


FIG. 1. RESEARCH POST

of the main muscle groups was measured (muscles actuating the hip, knee, shoulder and elbow joints and the torso) in statics, assuming the commonly accepted joint angle values between segments, and observing the standard procedures [18-20,24].

The stand for measuring the force applied by the rower to the grip during rowing included the Concept II type C rowing ergometer (Fig. 1). The Concept II type C ergometer is the most frequently used device for training and research in rowing [13,15,35,38,45,48]. A force transducer was attached (working in the range of 0-2 kN, 50 Hz) between the grip and the chain. The course of the rowing was filmed by two 50 Hz camcorders. The task for the rowers was to do 3 series of 10 strokes each with the maximum force at the stroke rates of 32 c/min, 36 c/min and 40 c/min. This rate corresponded to the range applied during races. In the first five cycles they were expected to reach the requested rate. In the next five cycles, which were recorded rowers were asked to maintain it. The series were separated by a two-hour pause. Using the recorded films and the Vidana package (Germany), spatial coordinates for the points studied were calculated. The resulting time courses were filtered by using a fourth-order Butterworth low pass filter with cut off at 4 Hz. They contained full rowing cycles, with the addition of 7 previous samples and 7 following the cycle, which were removed after the inverse dynamics problem was solved.

With the Dynamic Analysis Design System package (DADS) (LMS, Belgium), models of rowers were built; assuming that during rowing on the ergometer both sides of the body executed a symmetric motion. The rowers' spatial models were composed of 18 rigid bodies linked by ^{5th}-class 18 kinematic pairs (16 rotational and 2 translational) representing left side of the human body (Fig. 2).

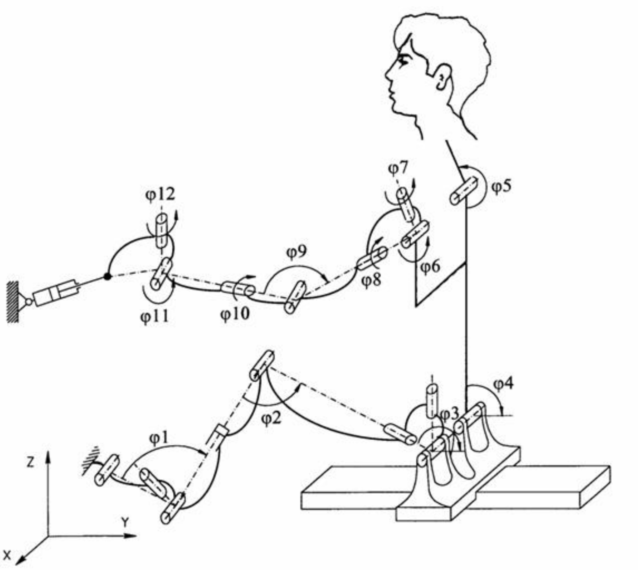


FIG. 2. MODEL OF A ROWER IN THE DRIVE PHASE

The total mobility (number of degrees of freedom) can be estimated according formula [53]:

$$F = 6 \cdot N - \sum_{i=3}^{5} i \cdot j_i$$

where F is the mobility of the body, N is the number of movable bones, i is the class of the joint, and j_i is the number of joints of the class i. According to this formula, the total mobility of the model is:

$$F = 6 \cdot 17 - 5 \cdot 18 = 12$$

The inertial parameters of the model segments were calculated on the basis of regression equations [52]. Then net joint moments were calculated from the measured kinematic and kinetic data using three-dimensional body models of rowers' left side. The equations of motion are written by DADS [14] as:

$$M \cdot \ddot{q} + \Phi_q^T \cdot \lambda = Q^A$$

where M is the inertia matrix, q is the vector of all generalized coordinates, defining the positions and orientations of all rigid bodies with respect to some inertial reference system, Φ is a vector of constraint relations with Φ_q representing its Jacobian matrix, λ is a vector of Lagrange multipliers associated with the constraint reaction forces, and Q is the vector generalized forces. The Lagrange multipliers uniquely determine the torques that act in the system. These torques represented net joint moments actuating studied joints during rowing. Details of used methods are described by Jaszczak [22,23].

Treating the measurement result for the torque of the muscle group studied in statics as 100% of the strength capacity, it was compared with the values obtained during rowing, with the same joint angle between the studied segments, and thus estimating the degree of the utilization of the strength potential for the 32 c/min, 36 c/min and 40 c/min stroke rates. Differences in strength potential and its utilization were tested for significance between the two crews using a t-test analysis.

Finally all profiles of the moment of force were time normalized to 100 % of cycle to compare the technique of rowing among groups and stroke rates using a t-test. The t-tests were made for each sample separately to find fragments of the cycle where the differences were significant.

RESULTS AND DISCUSSION

Maximum torque values for main muscle groups of the rowers studied in statics are shown in Table 1. Although elbow flexors and extensors as well as torso flexors in high class rowers are clearly stronger, only the difference between the force potential of the elbow extensors in rowers belonging to the first and the second crew was statistically significant ($p<0.1$). The degree of (isometric) strength

TABLE 1. MAXIMUM TORQUE OF THE MAIN MUSCLE GROUPS [AVERAGE ± STANDARD DEVIATIONS] IN HIGH CLASS ROWERS AND INTERMEDIATE CLASS ROWERS

Joint		M [N·m] $\overline{x}$ ± SD	
		High class	Intermediate class
Elbow	F	93.37±12.56	78.25±9.92
	E	62.25±4.17*	47.25±5.98*
Shoulder	F	80.37±9.32	80.50±11.16
	E	102.00±26.44	103.75±4.94
Knee	F	148.00±43.20	155.00±22.28
	E	322.87±46.57	342.00±70.67
Hip	F	114.12±10.27	119.62±13.64
	E	559.50±123.12	556.12±36.32
Torso	F	221.25±14.70	188.75±48.95
	E	562.25±111.82	548.00±75.05

Note: F- flexion, E- extension, * - statistically significant at the $p<0.1$

potential utilization in rowers during rowing at an increasing stroke rate is shown in Fig. 3. The degree for elbow extensors and knee and torso flexors (stroke rate of 36 c/min) was not estimated, as the net joint moment at the angle positions analyzed between segments indicated the involvement of antagonist muscle groups. The degree of utilization of the potential of the shoulder extensors diversified both the groups significantly ($p<0.1$) at the studied stroke rates.

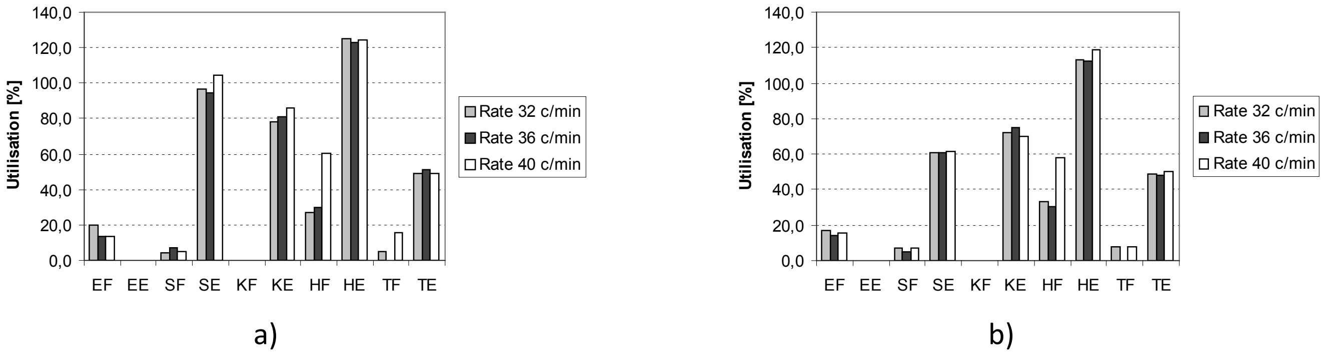
Fig. 4 demonstrates the rowing technique of high class rowers at an increasing stroke rate. A comparison between the courses of the muscle torque developed by large muscle groups within both classes of rowers showed significant differences ($p<0.1$) only in the knee joint at the end of the recovery phase at the 32 c/min stroke rate. That is why in order to determine the differences between the rates the size of the sample was increased by combining the ^{1st} group with the ^{2nd} one.

Significant differences ($p<0.1$) in the courses of the muscle torque between the rates of 32 and 36 c/min appeared in most of the joints (except for the elbow joint and wrist joint), and their largest concentration was recorded at the beginning and the end of the recovery phase. Further on, a comparison between the rates of 36 and 40 c/min allowed us to observe differences from as early as one third of the cycle duration (places of occurrence of large joint maximum values) to two thirds in the case of the ankle joint, whereas in the case of the knee joint, hip joint and torso, after a short pause, they were continued until the end of the cycle. At extreme rates the above-mentioned joints displayed similar differences, but they lasted without pauses from one third until the end of the cycle. The shoulder joint (as the only one) presented a difference from as late as one half of the cycle, while in the case of the elbow joint and the wrist joint the difference oscillated in the middle of the cycle between the rates of 36 and 40 c/min as well as between 32 and 40 c/min.

Yoshiga and Higuchi [51] report that rowing performance increases with body size. In this case the height of the rowers studied was similar, while only their body mass differed. Relations between body mass and the isometric force [44] are to be noticed only in the weaker muscle groups, which play a smaller role in propelling the boat. Although the torque values obtained in statics turned out to be generally smaller than for the rowers studied by Janiak et al. [21], the sequence of muscle groups in terms of the force developed was analogous. They are also lower than the torque values generated by team game players, namely handball, volleyball and basketball players [5,18]. Nevertheless, a deeper analysis of the tested person's characteristics reveals that these players were taller and heavier, which confirms the relation between the torque developed and the body mass.

The main muscle groups in a rower should be divided into two types in accordance with their function during the rowing cycle:
1. muscles directly involved in propelling the boat: knee extensors, hip extensors, torso extensors, shoulder extensors, elbow flexors,
2. muscles responsible for the course of the recovery phase: knee flexors, hip flexors, torso flexors, shoulder flexors, elbow extensors,

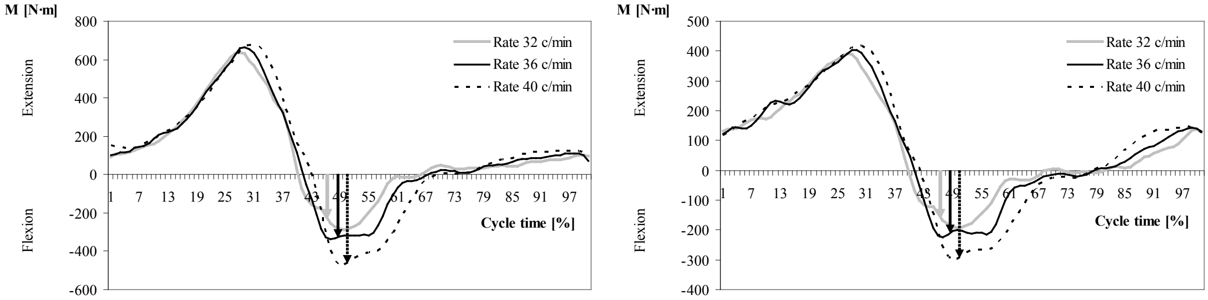
The groups of the first type are stronger than their counterpart groups. Also, the extent to which they utilize the strength potential during motion (at the assumed joint angles) is higher. This can be



a) b)

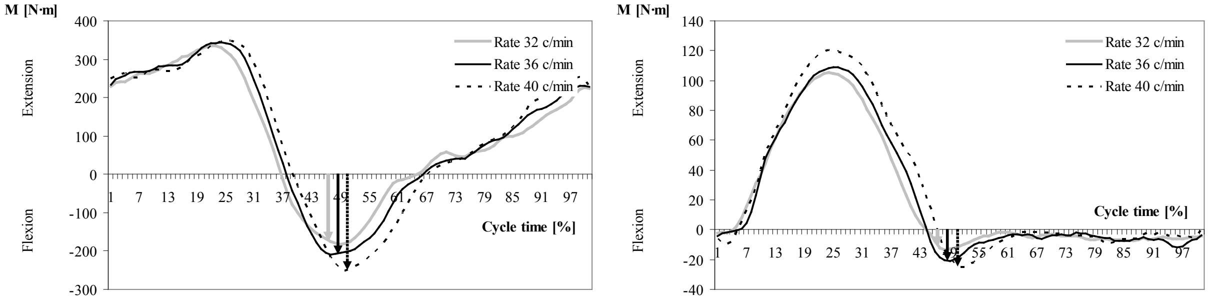
FIG. 3. THE DEGREE OF STRENGTH POTENTIAL UTILIZATION IN HIGH CLASS ROWERS (A) AND INTERMEDIATE CLASS ROWERS (B) WHEN ROWING AT THE 32 C/MIN, 36 C/MIN AND 40 C/MIN STROKE RATES.

Note: *EF-elbow flexors, EE-elbow extensors, SF-shoulder flexors, SE-shoulder extensors, KF-knee flexors, KE-knee extensors, HF-hip flexors, HE-hip extensors, TF-torso flexors, TE-torso extensors*



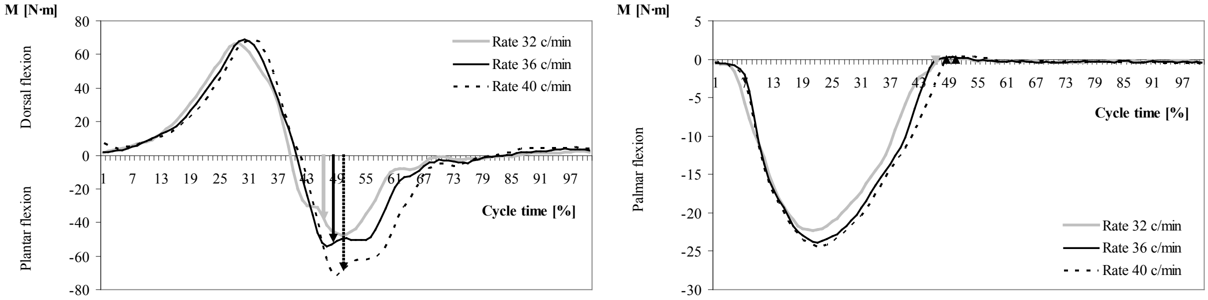
a) Hip

b) Knee



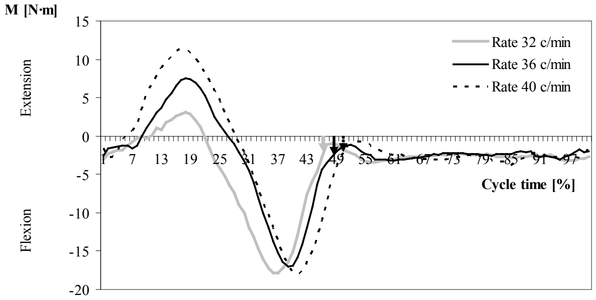
c) Torso

d) Shoulder



e) Ankle

f) Wrist



g) Elbow

FIG. 4. NORMALIZED NET JOINT MOMENT ACTUATING HIGH CLASS ROWERS STUDIED JOINTS DURING ROWING AT STROKE RATES: 32 C/MIN, 36 C/MIN AND 40 C/MIN; A) HIP, B) KNEE, C) TORSO, D) SHOULDER, E) ANKLE, F) WRIST, G) ELBOW.
Note: vertical arrows indicate the end of the drive phase and the beginning of the recovery phase for a given stroke rate.

explained by the fact that at these joint configurations, the studied muscles are forced to overcome the external resistance force on the grip at its near-maximum value. This force is absent during the recovery phase. Negative torque values developed by some muscle groups of the second type (elbow extensors, knee flexors, torso flexors) confirm that their antagonists (which perform an eccentric work) are more involved at the moment of assuming the set joint angles in the recovery phase.

An optimal solution to calculate the degree of the utilization of the rowers' strength potential would be to assume identical angles in the adjacent joints during the measurements in statics and dynamics. However, it was only a solution of the inverse dynamics problem that informed us about their values during rowing, whereas delaying the potential measurement until that time would require that part of the research to be performed in a completely different stage of the rowers' preparation cycle.

The magnitude of the utilization of the (isometric) strength potential during rowing pointed to hip extensors as the leading group in both high class and intermediate class rowers, regardless of the rowing rate. Moreover, they displayed the largest strength potential.

A comparison of the absolute values of angular velocity during rowing at the angles studied suggests that multi-joint muscles could work eccentrically, so the degree of the strength potential utilization could reach values exceeding 100%. This is confirmed by the results obtained by Krakor et al. [33], who studied electromyograms (EMG) of rowers' large muscles in statics and dynamics. They recorded a higher activity in the case of latissimus dorsi, erector spinae during rowing. This same trend for latissimus dorsi, triceps brachialis and serratus interior was observed by Jobe et al. [25]. Their activity in dynamics amounted to, respectively, 135%, 121%, 226% of the values measured in statics.

Besides, the high values of the degree of strength potential utilization should be treated as a postulate of the domination of dynamic strength exercises in rowers' training, because it is they that mainly improve muscle dynamic strength (18%), and not muscle isometric strength (9%) [41]. At the same time we could also assume that for the studied rowers rowing was an automated motor activity, during which the optimal number of motor units was recruited in motion-inducing muscles. As a consequence, it should be assumed that in dynamics at specific stages of motion, this number must be slightly smaller than the number which is needed in order to generate maximum muscle torques in statics.

A notable fact is that the values for shoulder extensors in high class rowers almost doubled those of intermediate rowers, which may indicate a relation between this phenomenon and the rowers' sport class.

A quantitative description of the rowing technique, which means a description with the help of time courses of the torque of muscle groups actuating large joints, agrees with verbal and visual descriptions found in literature [1,8,28] as well as with EMG patterns [13,40,50]. There is an exception for the elbow joint actuators. The rower starts the cycle by catching the oar and straightening his legs and torso. As early as at the very beginning, the torso extensors generate a considerable torque that dominates the torque produced by the knee and hip extensors. The other groups only begin to get involved at that time. Thanks to this the torso allows for a transfer of the forces applied by the lower limb muscles to the oar. Most of the muscle groups tested generate the maximum torque at one third of the cycle, but the boat speed is minimal at that time [2,46,47]. Then, the involvement of the extensors decreases in favour of the flexors (the boat speed increases) which reach the maximum value at the time of the beginning of the release phase. This is because then the rower pushes the oar away from his body and begins to move in the opposite direction. At two thirds of the cycle the rower begins to curb his forward movement, which is indicated by the torque generated by hip, knee and torso extensors. The end of the cycle is usually marked by the boat reaching the highest speed [37,46,47], with torso extensors generating over 50% of the maximum torque value.

A separate description is necessary for the course of the torque of the muscle group that controls motion in the elbow joint during the drive phase, which initially demonstrated the involvement of these joint extensors, and at one fourth of the cycle changed into a value that corresponded to flexors' activity. The phenomenon observed depends on the position of the direction of the resistance force applied to the handle in relation to the elbow joint rotation axis. When the direction of this force ran below the elbow joint rotation axis (which was recorded in the first part of the drive phase), it generated a torque in relation to that axis making the elbow joint flex. The rower, pulling the grip towards his torso along the optimal (shortest) trajectory, eliminated its excessive value by involving elbow extensors (Fig. 5a). The situation was reversed in the second part of the drive phase. The direction of the resistance force applied to the handle ran above the elbow joint axis, which led to the production of a torque extending the elbow joint and was overcome by elbow flexors (Fig. 5b). The above-described phenomenon takes place mostly during rowing on the ergometer, when there is no motion related to catching the oar (lifting the rowing handle), following which the direction of the resistance force applied to the handle runs above the elbow joint rotation axis.

Relative duration of the drive phase and recovery phase did not change along with the increase in stroke rate, just like the time of the extremes in the studied muscles. Therefore, cycle shortening occurred at the expense of reduction within both the phases at

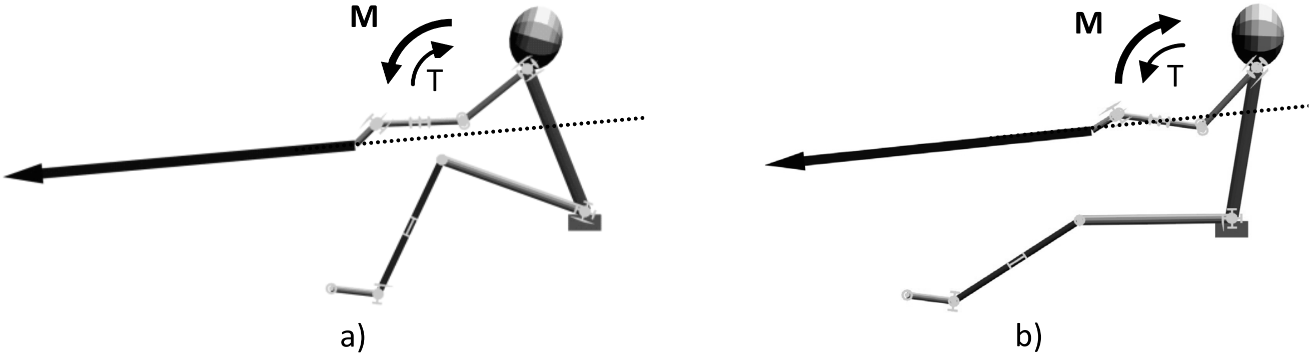


FIG. 5. SENSE OF THE MUSCLE TORQUE INDUCING MOTION IN THE ELBOW JOINT DURING THE DRIVE PHASE, WHEN THE DIRECTION OF THE RESISTANCE FORCE APPLIED TO THE HANDLE RUNS BELOW THE ELBOW JOINT ROTATION AXIS (A) AND ABOVE THE AXIS (B).
Note: M – torque of the muscles actuating the elbow joint, T – torque of the resistance force applied to the handle

the same time in both groups of rowers. Differences between rates occurring mainly at the moment of transition from the drive phase to the recovery phase resulted from an increase, along with the stroke rate, in the maximum flexor torque that was generated at that time, enabling the rower to finish the drive phase and quickly push the oar away from the body. This in turn resulted in the rower's forwards movement. Recovery should be started with a small, regularly growing speed of the cart, thanks to which boat speed fluctuations will be smaller [46], and the drive will be more efficient [36,49]. Higher rowing rates are more favorable, because boat speed oscillations are smaller. However, more effort on the part of the rower is necessary [4].

A lack of statistically significant differences between the rowing technique of different sport class rowers does not mean that there were no such differences, but is rather a result of a large diversity within each of the groups [23]. Therefore, the existence within one crew of similar F(t) characteristics does not mean that the same must be true for the large joint M(t) courses.

M(t) courses for muscles operating the rower's large joints appear to be a better criterion for crew selection, especially in the case of high class rowers, as they provide more detailed information on the technique than the F(t) measured on the oar do. As a consequence they allow for a more accurate selection of crew members. Moreover, they guarantee identical performance of the motion, which in the case of multi-person crews bears a special importance, as each rower copies the motions of the one in front of him or her. The coaches' knowledge of which muscle groups dominate in individual cycle phases will help them rationally modify and unify the rowers' technique as far as differences are concerned. It also help to adapt the boat's rigging to their body build and M(t) characteristics, in order to provide maximum sustainable power during stroke and improve sport results.

CONCLUSIONS

Results of theoretical and experimental research conducted within this study bring the following conclusions:

1. M(t) profiles of the studied muscle groups indicate that hip and knee extensors as well as torso extensors and flexors have a crucial influence on the effect of making the boat move.
2. The degree of potential strength utilization of individual muscle groups suggests that rowing results will be particularly improved by increasing the strength of the muscle group that is used the most, which is hip extensors.
3. The fact that differences in the torque courses for the studied muscle groups between the imposed stroke rates occur mainly at the transition from the drive phase to the recovery phase indicates that this is the stage of the cycle whose examination will be the most diagnostic from the point of view of developing a quantitative description and assessment of the rowing technique.
4. Using the M(t) profiles, generated by large muscle groups during rowing, as guiding parameters will allow for an optimal selection of a high class crew.

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