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Selected biomechanical aspects of the asymmetrical loading of the human postural system when riding the C1 speed canoe and their influence on the development of muscular imbalances

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Abstract

OBJECTIVES: The main aim of this study was to analyse selected biomechanical aspects of the asymmetrical loading of the human postural system when riding the C1 speed canoe and their influence on the development of muscular imbalances.
METHODS: 3D kinematic analysis of a simulated forward stroke of the canoeist in a pool with a counter-current (N = 9) and analysis of MRI data with selected individuals (N = 5), videoanalysis of actual paddling top athletes (N = 12), the kinesiological analysis of movement.
RESULTS: Can be stated that when riding a C1 speed canoe the postural system is exposed to two types of asymmetric loading. In the first place, there is lateral asymmetry, which stems from the very nature of the one-sided paddling on this type of vessel. The canoeist has to compensate for the consequent instability by shifting the body's centre of gravity higher above the kneeling lower limb. This effect is achieved by the so-called pelvic lateralisation from the paddling side and by this side's skewing to the kneeling lower limb. Another asymmetry is connected to the forward-backward body movement and its time-dependent deviation from the neutral posture. A significant disproportion between generally fixation movements of the lower part of the body and phasic movements of the upper part of the body has been confirmed. These asymmetrical positions result in a significant unilateral overloading of the quadratus lumborum on the side of the supporting lower limb (side without the paddle), as well as an overloading of the spine straighteners in the lumbar area, in particular on the part of a supporting lower limb,

ORIGINAL ARTICLE

and bilateral yet asymmetric overloading of m. iliopsoas, which in addition takes place in different isometries. The analysis of MRI data indicates that, during longitudinal training, lateral disproportion in the volume and intensity of postural system loading is the cause of different cross sections of the iliopsoas muscle and quadratus lumborum muscle on the side of the kneeling and supporting lower limbs. With both muscles, larger cross sections with a statistical significance level α = 0.05 and thus also strength on the side of the supporting lower limb can be expected.

CONCLUSION: When canoeing on the C1, a significant unilateral overloading occurs with m. quadratus lumborum on the part of the supporting lower limb (side without paddle). Furthermore, spine straighteners in the lumbar area are overloaded, in particular in the part of the supporting lower limb. Last but not least however, the bilateral asymmetric overloading of m. iliopsoas occurs.

INTRODUCTION

Flatwater canoeing is a world-renowned sport discipline with an Olympic tradition. Every year races in this sport are held as a part of the World Cup, and with the exception of Olympic years, also as a part of world championship races. The reasonably large membership base, together with the well-established methodology of the training process, enable the systematic extension of knowledge about this sport discipline using objective methods. Within the broader context of knowledge, it is very important both in terms of the issue of an increase or stagnation in the performance level of top athletes and with respect to eliminating risks of musculoskeletal overload, especially with children (Kolarova *et al.* 2019) and young people.

Riding on a speed canoe requires the athlete to kneel on one knee in the boat. The second lower limb serves as a support and is crouched in front of the body to ensure posture stability (Carr & Shepherd, 1989). Canoeists always paddle on the side of the kneeling lower limb using the forward-backward movement of the whole body (Rynkiewicz *et al.* 2013). The single bladed paddle is used for locomotion (see Fig. 1). At present, (Čichoň & Doležal, 2006; Carneiro & Castro, 2009) and other authors examining the canoeing in their works divide the forward stroke into four phases. They are the catch phase, pull phase, exit phase with throwing, and the final transmission phase (see Fig. 1).

According to Robinson *et al.*(2002), the catch phase accounts for 20–26% of the total stroke length, the pull phase for 26–46%, the exit phase between 0–20% and the transmission phase for 25–35%.

The stroke frequency itself depends on the course length or the training pace intensity. According to (Zahálka *et al.* 2011), the racing track pace tends to be 55–67 strokes per minute and the starting rate about 86 strokes per minute. Top canoeists start racing with as many as 180 strokes per minute (Robinson *et al.* 2002). Of course, the paddling pace depends both on the length of the course and on the physical fitness of a canoeist.

From the point of view of human motor activity, speed canoeing presents artificial locomotion given the cyclical movement of almost all body segments. Compared to natural bipedal locomotion, i.e. with the imaginary peak of the phylogenetic development of human locomotion, the following abnormalities can be identified with this movement pattern. The lower limbs, mounted to the bottom of the boat by means of permanent contact, perform a predominantly postural function associated with the transmission of propulsive forces. On the other hand, the upper limbs and associated segments of the axial system are the movement generators. In terms of the economics of muscle work, paddling is a highly intense physical activity, asymmetrically distributed according to both the transverse and sagittal planes of the body. The locomotion system of humans is not primarily adapted to such an atypical movement – neither from a kinesiological nor from a biomechanical points of view. With the growing volume and intensity of the training efforts (Wilk *et al.* 2018), the risks of so-called unilateral overloading have also been growing, in particular of the axial system of a canoeist (Campbell-Kyureghyan *et al.* 2005)

The asymmetrical body position, together with a particular paddling technique, generates asymmetric muscle work (Rynkiewicz *et al.* 2013). As paddling on both sides during the C1 training by a competitor is not usual, the paddling always only takes place on the right or left side of the boat. This process of long-term specialised training may result in the asymmetrical mass and static tension in an athlete's muscles (Sanchis-Moysi *et al.* 2011). From the kinesiological point of view, there is a risk of muscle imbalances (Page *et al.* 2009). This fact has also been confirmed by study by (Humphries *et al.* 2000), which confirmed the relationship between the occurrence of muscle imbalance and paddling technique. As far as other sports disciplines are concerned, (Hides *et al.* 2010), for example, describes the imbalance of m. iliopsoas and m. quadratus lumborum among Australian top football players. The asymmetry of the works of muscles, in particular with m. iliopsoas and mm. glutei with tennis and football players has likewise been shown in a study by (Sanchis-Moysi *et al.* 2011).

If unilateral training in any sport persist for a long time, somatic dysfunction or so call functional joint block (Piglova *et al.* 2017) and structural changes in the musculoskeletal system might occur (Šifta, 2018). With the axial system, the issue in particular is a significant, already non-physiological curvature of the spine in the sagittal plane, which causes overloading of vertebrae and intervertebral discs (Keller *et al.* 2005). In addition, deepening of the lordotic and kyphotic curvature of the spine also impairs its general stability (Smith & Fernie, 1991). This problem increases with the intense and unsuitable training (Gallagher *et al.* 2016; Rusko, 2003;

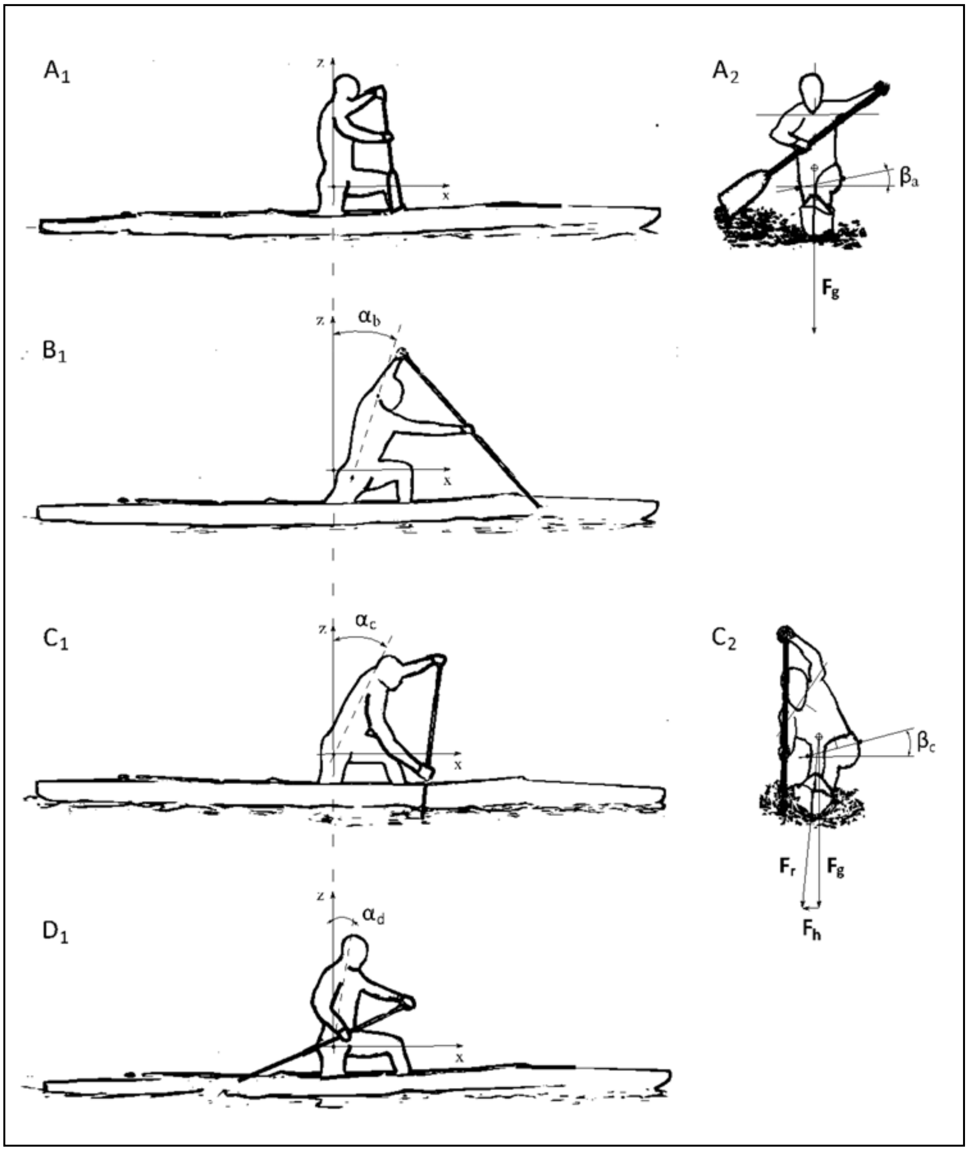

Fig. 1. C1 speed canoeing in various phases of the forward stroke (source: own)
Legend:
$A_{1,2}$ - Neutral position (transmission phase of stroke)
B_1 - Position with the maximum body forward extension (catch phase)
$C_{1,2}$ - Position in the active stroke phase (pull phase)
D_1 - Position at the exit (stroke completion phase)
⊕ - Centre of gravity of body (COG)
● - Marker indicating trochanter major femoris
Fg - Gravitation force vector
Fr - Resulting force vector (Fr = Fg + Fh)
Fh - Horizontal force vector
αi - Body inclination angle in relation to the straightened body position when kneeling
βi - Angle of hip joints skewing with the kneeling body
- Indexes $i \in \{a,b,c,d\}$ represent the belonging to A, B, C, D figures.

Wojtys *et al.* 2000). The permanent overloading of the general postural system may lead to the occurrence of the so-called low back pain syndrome (Cholewicki & McGill, 1996; Harrison *et al.* 2005). As studies by Kameyama *et al.* (1999), Abraham & Stepkovitch (2012) or Haley & Nichols (2009) have confirmed, this is a wide-spread problem with canoeists.

PURPOSE OF RESEARCH

Considering the finding above, we should mention the fact that there have generally been very few studies dealing with the mechanical conditions of paddling (Fleming *et al.* 2012). Some of the studies made since 1970 describe measuring kinematic and kinetic data with the use of the biomechanical analysis (Michael *et al.* 2012). They are in particular laboratory studies on simulators, which simulate riding on the water surface. We have been unable to find a study focusing on a biomechanical analysis of the forward stroke on C1 regarding any possible postural system overloading. For this reason, the main goal of the study is – on the basis of the synthesis of current knowledge and using our own experimental case study investigations – to analyse selected biomechanical aspects of asymmetric loading of the postural system while riding the C1 canoe in flatwater canoeing. The following research questions have been formulated. How does the asymmetrical loading of the postural paddling system on the C1 canoe in flatwater canoeing arise? Can long-term training of the riding C1 canoe in flatwater canoeing affect the asymmetrical distribution of the muscle mass with selected muscles of the postural system? In this respect, the research is focused on m. iliopsoas and m. quadratus lumborum.

METHODOLOGY

Research group characteristics

The study has been designed as a double case study. The research group consists of two groups of canoeists. The first group intended for the 3D kinematic analysis of the stroke, consisted of a total of 9 canoeists (5 with the left and 4 with the right kneeling lower limb). In terms of their age, the subjects ranged from 26–45 at the time of the experiment. They were canoeists with the many years of experience in racing (more than 15 years) both at national and international levels. The body height of subjects ranged from 175 –190 cm and their body weight ranged from 74–90 kg. Due to organisational and financial reasons five subjects in total have been chosen from this group to study morphological changes in muscles using MRI.

Another group intended for the analysis of real forward strokes on the C1 and the verification of obtained experimental results consisted of 12 subjects in total. These were professional canoeists, who are among to the best canoeists in the world between 1996 and 2018. At the time, videos were shot, the age of observed individuals was between 22 and 33. Over 60% of these paddlers in this selection met at European or World championships or Olympic Games on a regular basis.

Ethical clearance

Approval was received from the participating institutions during application process to grants PROGRES Q41 and TG01010117 – PROSYKO. All evaluated subjects agreed to participate voluntarily and signed written informed consent according to Declaration of Helsinki.

Experimental methods

An optoelectronic system Qualisys combined with the Qualisys Track Manager compatible software was used for 3D kinematic analysis of the canoeist's movement during paddling. Nevertheless, this technology is not sufficiently accurate in cases spanning over a large area. As the predetermined distance of cameras from the monitored object during the entire recording period (several meters) had to be maintained, it was not possible to monitor canoeing on C1 directly on the open water surface. Therefore, on the basis of the study by (Michael *et al.* 2012), in which the authors used the paddling ergometer, an approach was chosen to use the swimming pool with the counter-current. Subjects were kneeling and paddling on the swimming pool's edge raised approx. 10 cm above the flowing water surface. This situation simulated the actual canoeing experience, at least from the point of view of resistance forces on the paddle. At the same time negative aspects related to the ergometer riding were eliminated. To record subjects' movements, 12 cameras with 100 Hz recording frequency were used. Their distance from the scanned object did not exceed 4 m; during the calibration, the orientation of spatial coordinates was set so that a kneeling canoeist looked in the positive direction of the x-axis, and the positive direction of the z-axis was oriented vertically upwards. The y-axis perpendicular to the other axes was oriented so that its positive half-axis was directed to the side of the kneeling lower limb, i.e. to the paddling side.

On each recorded subject, skeletal point were palpated, the projection of which through the skin cover does not change with movements of the person. Forty-one markers in total were placed on the body. The obtained data points were used to create the human body model. The created anthropomorphic mechanism consisted of fourteen segments. It meant the head with a neck (5 data points), a chest (9 points) and three segments for each limb (3–4 points). Using (Zatsiorsky *et al.* 1981), the centre of gravity of individual segments, consequently the position of the general centre of gravity (COG) of the body and the centre of gravity of the upper half of the body were determined. To determine the orientation of the pelvic bone in the space (anteversion, skewing), 4 points were used (2x spina iliaca post. sup. and 2x spina iliaca ant. sup.). The axis of hip joints was given by the join of the major femoris trochanters. The axis of the shoulder joints was defined by the acromion join. The orientation of the head is described by the join of the centres of temporal bones. The axis of the body was defined by the join of centres of axes of shoulder and hip joints. The angle α was introduced as an inclination of the body axis toward the vertical z-axis (in the lateral projection to the xz-plane). Skewing hip joints (angle β) was defined as a deviation of the hip joints axis from the horizontal plane (in the projection to the yz-plane).

As the results from the 3D kinematic analysis had to also be verified the actual canoeing on the free

Tab. 1. Estimate of the stroke proportionality with the paddling frequency of 27/min. (N = 9, α = 0.05).

Stroke phases		catch	pull	exit	transmission	total
Absolute (s)	Average	0.18	0.99	0.20	0.85	2.22
	SD	0.08	0.09	0.02	0.20	0.21
	CI	±0.05	±0.06	±0.01	±0.12	±0.13
Relatively (%)	Average	0.079	0.446	0.091	0.383	1.000
	SD	0.037	0.042	0.007	0.089	0.095
	CI	±0.023	±0.026	±0.005	±0.055	±0.059

Legend: SD – standard deviation; CI – confidence interval; Relative values are related to the average of the total stroke length.

surface was analysed. For this purpose, ten freely available videos in total (YouTube) were analysed showing members of the first group canoeing at 200m, 500m and 1000m distances at a racing pace. Mostly, these were records from races in World Championships and Olympic Games. Other video-sequences were chosen from the educative record of the C1 canoeing technique. The total length of the analysed video footage was 47 minutes. As the canoeing footage includes side, front and rear views, it was also possible to perform a simple 2D videographic analysis of the range of motions of main body segments and phasing out of the shot into individual sections. In an attempt to make the described acts more illustrative, four pictures of a canoeist in various stroke phases were exported from videos. These were consequently converted into a better arranged graphical layout/design (Fig. 1)

Within the morphology analysis, MRI was used with selected individuals to compare cross sections of m. iliopsoas and m. quadratus lumborum. This experiment was implemented on the Philips Achieva 1.5T device with the surface fifteen channel spinal coil. The weighted T2 sequence was selected, in particular T2 TSE in the axial plane, the section thickness of 3 mm. The cross sections of muscles were obtained automatically using image processing SW, which is incorporated into the MRI device. The muscle section was made in the transversal plane at the L3 and L4 level.

Statistical analysis

Estimates of the stroke proportionality and shapes of its kinematic geometry have been made as follows. With each subject from the experimental group (N = 9) 10 strokes in total have been analysed. On the basis of the dispersion analysis, it has been found that with monitored quantities the dispersion between individuals accounts for more than 70% of the total data dispersion. Therefore, for each monitored quantity and each subject, the arithmetical average from ten strokes was calculated at first. The point estimate of the mean value of the given quantity was then construed as the arithmetical average from these arithmetical averages. The data variability has been described by the standard deviation (SD) calculated from the intergroup dispersion. Resulting confidence intervals (CI) were built on the statistical significance level $\alpha = 0.05$. Figures 2 and 3 define the confidence interval as a normal to the hysteresis curve of the cyclogram. In order to make the information on individual subjects movements comparable, the data have been converted so as to correspond to movement of a person with the height of 185 cm.

Within the statistic processing data from MRI related to muscle cross sections, the following procedure has been chosen. At first, descriptive statistics were counted for a given sample group, in particular location and dispersion indicators. In terms of the parametric approach, they are the arithmetic average and the standard deviation. Due to the small size of the selection file (N = 5), data normality disruption could be expected. Therefore, their non-parametric alternatives, i.e. Median, inter-quartile range (IQR), maximum and minimum were also calculated. In this respect, overview box-plot charts were construed too. Consequently, the data normality was tested using the Sharpiro-Wil test. Furthermore, the Wilcoxon pair test has been chosen to prove the difference between muscle cross sections. To express the statistical significance of performed tests, the p-value was also used. To refuse the zero hypotheses the statistical significance of $\alpha = 0.05$ was chosen.

RESULTS

Stroke proportionality

The result section is opened with the estimate of the proportionality of stroke of the experimental group of subjects with a paddling frequency of 27/min. The estimate was made on the basis of the analysis of ten strokes, each of them in QTM. Table 1 indicates that the catch and exit phases are proportionally the shortest parts of the stroke cycle. Each of these phases lasts 6–10 % of the stroke cycle. Pull is the longest phase as it accounts for approximately 42–47% of the stroke cycle. The transmission phase accounts for approximately 33–44% of the stroke.

The stated findings generally correspond to Robinson *et al.* (2002). The catch phase is an exception, as it is approximately twice as long according to this source. Therefore, the results were also compared to Zahálka *et al.* (2011). In this case, where individual proportions of the stroke are as follows: catch phase – 10%, pull phase – 41%, exit phase – 10% and transmission phase – 38%, we can even talk about a very good correspondence, despite the fact that the study was devoted to the stroke analysis at a racing pace with a paddling frequency of approx. 41/min. On the basis of these findings, kinematic records can be considered representative in terms of the proportionality. In addition, the findings can be further utilised to increase the clarity of the cyclograms below.

Kinematic stroke geometry

At first we will focus on the analysis of the general centre of gravity of the body and the centre of gravity of the upper part of the body. Figure 2A showing the movement of both points in the lateral projection indicates the following. In accordance with the theory and video analysis (see Fig. 1) during the transmission phase, both centres of gravity move downwards and forwards behind the supporting leg. The opposite movement occurs in the stroke phase whereas when pulling the paddle in the water observed centres of gravity are closer to the water surface. Interestingly, trajectories of these points are the same from the morphological point of view. They only differ in terms of their extent. Therefore, extensive phasic movements of the upper

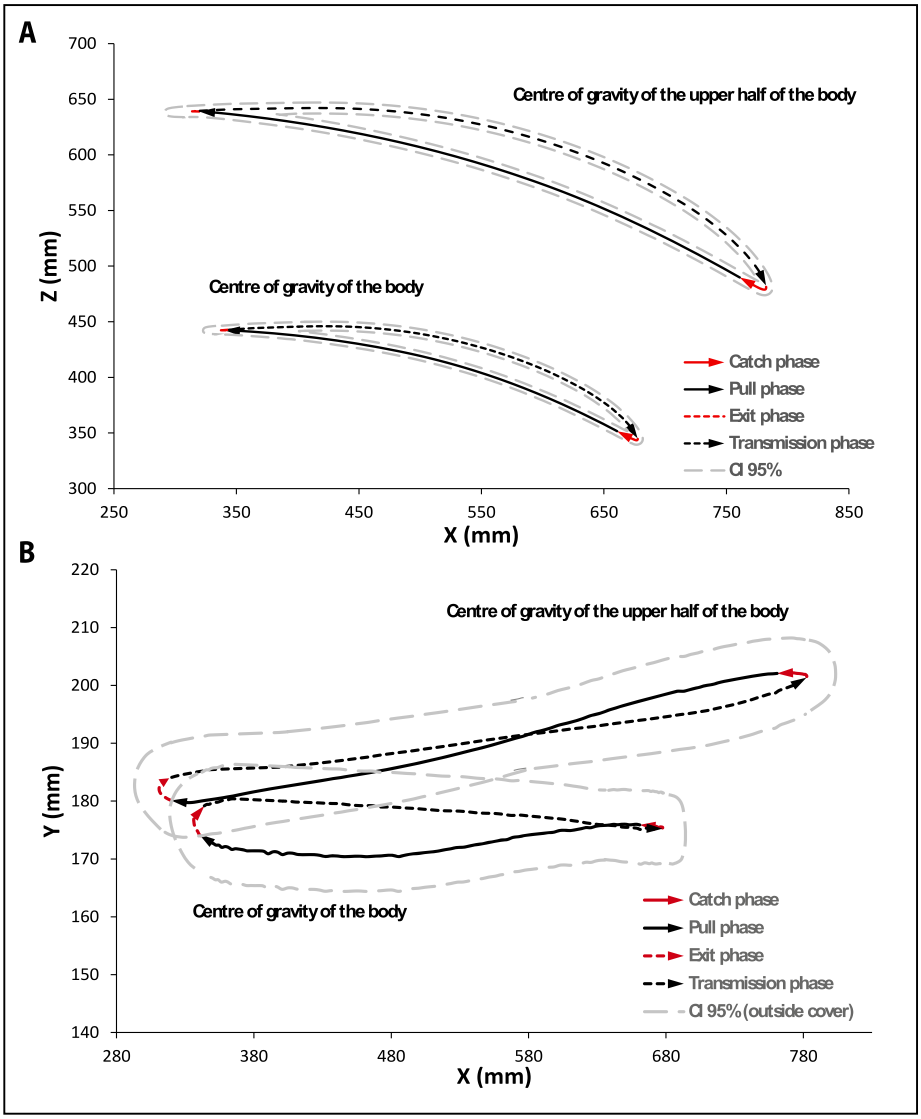

Fig. 2. Movement of the general centre of gravity of the body and the centre of gravity of the upper half of the body during the stroke on the speed canoe C1. (The scale of both axes is standardised with respect to the figure of a canoeist with a height of 185 cm). The canoeist looks in the positive direction of the x-axis and the positive half y-axis is directed at the paddling side.
A. Lateral projection (xz-plane).
B. Horizontal projection (xy-plane).

part of the body contrast rather static fixation movements of the lower part of the body.

In particular, the horizontal movement of both centres of gravity is worth noting (see Fig. 2B). First, what can be noticed is a relatively high variability of monitored paths. However, looking at the scale of the y-axis, it is obvious that it is only apparent. During the transmission phase, the general centre of gravity moves straight forward. Here it is worth noting that the experiment took place in a pool with a counter-current whereas a canoeist was kneeling on a 20 cm wide pool edge instead of being in a boat. Therefore, he/she could use the whole contact surface of the supporting lower limb's feet to stabilise the movement. For this reason, deviations in the trajectory of the general body centre of gravity projection into the horizontal plane from the direction of canoeing (x-axis) during the transmission phase of the stroke are physically possible. In the phase of pulling the paddle along the water, a slight departure from the general centre of gravity to the side of the supporting leg is seen. For the cause, refer to the force breakdown in Figure $1C_2$. During the active phase of the stroke, a resistive force is generated on the paddle, which the canoeist can use to compensate for the rotating effect of the gravitational force with the deviation of the gravity centre of the body from the vertical axis of the boat or the edge of the pool, as the case may be. The analysis of video-records confirms that this phenomenon becomes ever more obvious with the growing stroke intensity.

Looking at Figure 2B, it is obvious that the centre of gravity of the upper part of the body tends to depart to the paddling side during the catch phase. This tendency complies with the C1 canoeing techniques. In order for the canoeist to be able to strike the paddle perpendicularly to the water surface, it is necessary that the upper half of the body departs off the vertical axis of the boat to the paddling side. However, this deflection must be compensated for by deflecting the pelvis in the opposite direction, as it is obvious from Fig. $1C_2$, and also by its greater skewing to the kneeling lower limb, as indicated by the cyclogram of stroke phases

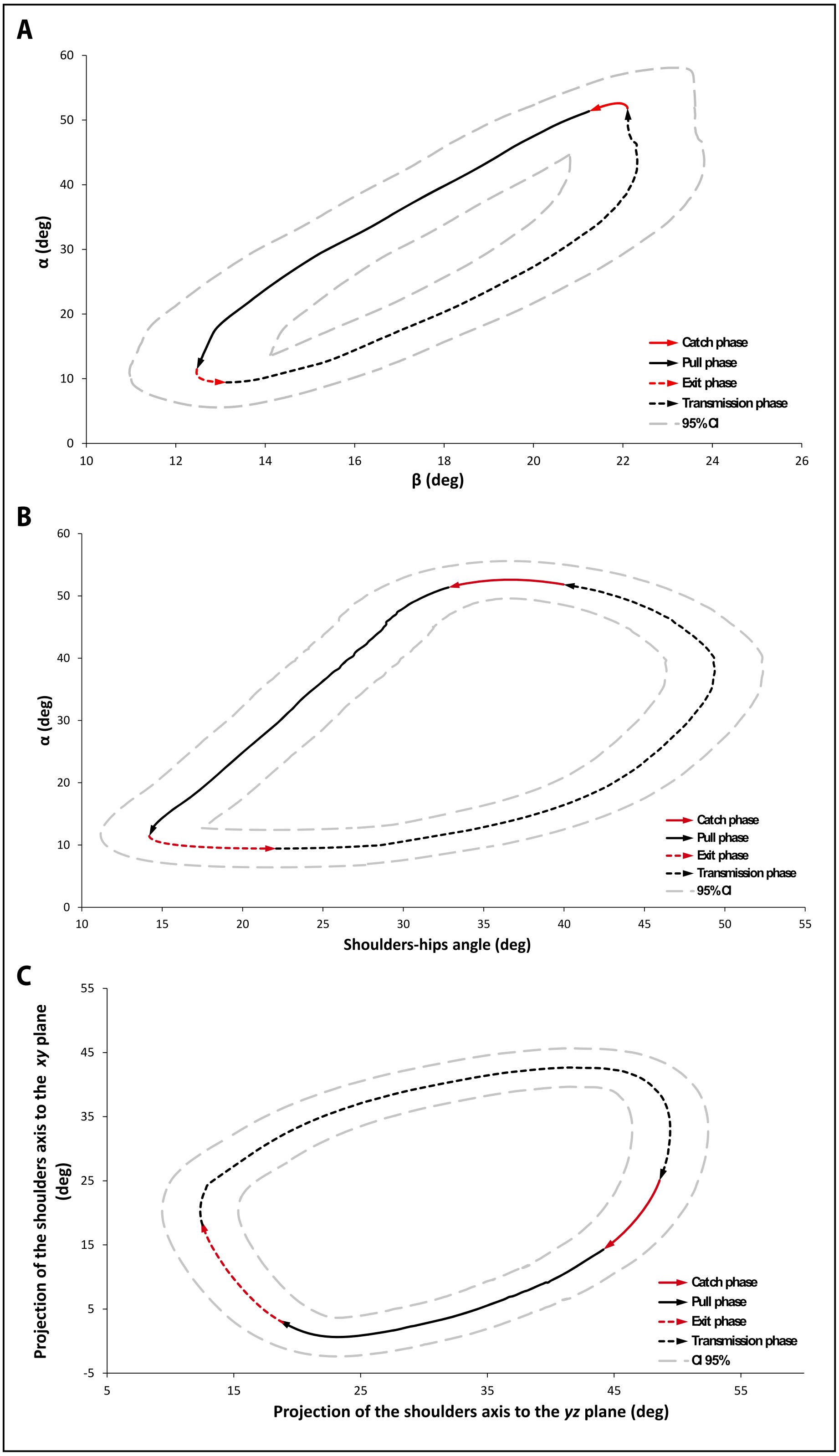

Fig. 3. Cyclograms of the stroke phases: A. Dependence of the angle α, of body inclination to the vertical z-axis, on the angle b, which represents skewing of the hip joints join (trochanters) in direction to the kneeling lower limb. B. Dependence of the angle a, of body inclination to the vertical z-axis, on the angle shoulders-hips, which include the projection of the axis of shoulders (join of acromions) and the projection of the hip axis (join of trochanters) to the xy-plane between each other. C. Dependence of the projection of the acromions axis to the xy-plane. A positive value of the angle of projection of the axis of the shoulders into the yz-plane means a rotation towards the kneeling lower limb. A positive value of the angle of projection of the axis of the shoulders into the xy-plane means a rotation behind the supporting lower limb.

(see Fig. 3A). Here the dependence of the angle α of the body inclination to the vertical *z*-axis) on the angle β (skewing the hip joints) is depicted for the canoeist kneeling. Furthermore, from the cyclogram in Figure 3A, it can be well seen that the angle β is smallest near the neutral position of the body, i.e. in the exit phase being approx. 12–13°. During other phases, this angle is always larger than upon the paddle exiting from the water. In the catch, phase its value even doubles in comparison with the minimum value. In addition, the hysteresis character of the cyclogram proves that in the phase of pulling the paddle along water, at first the

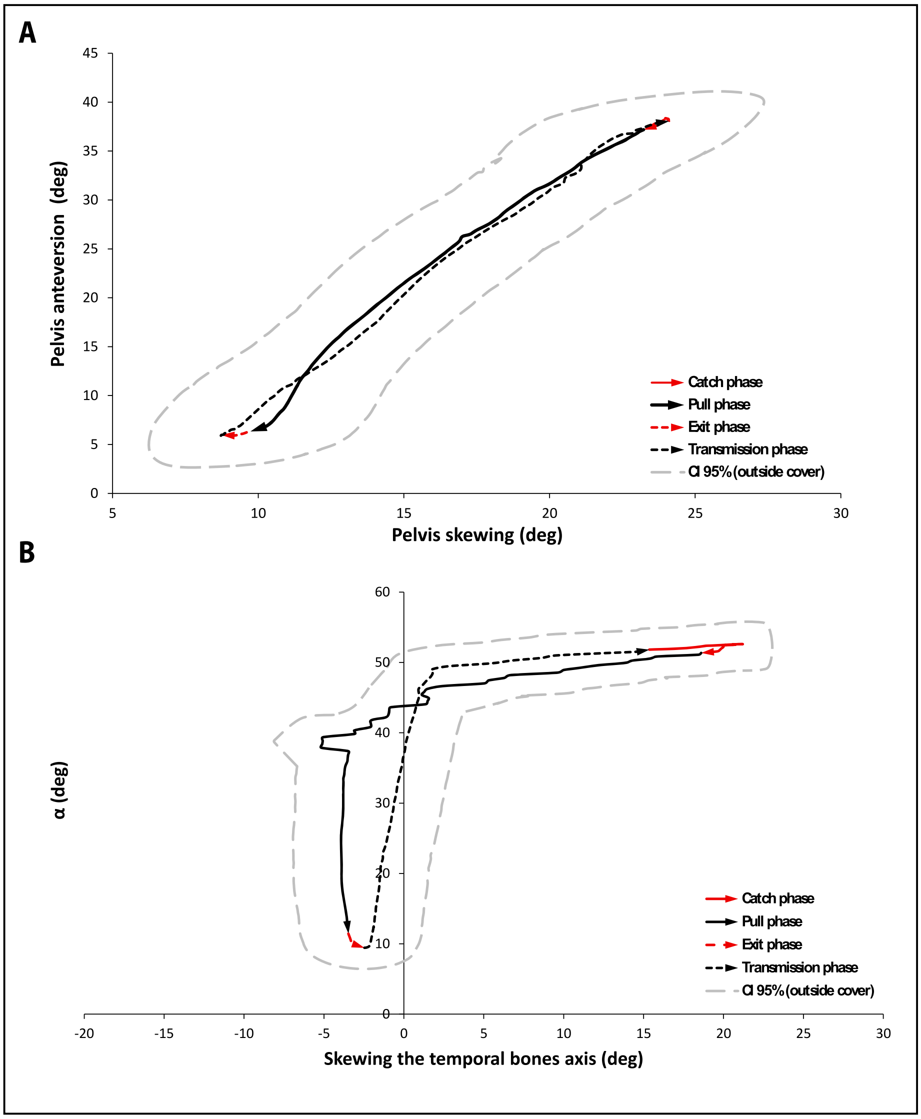

Fig. 4. Cyclograms of the stroke phases:
A. Dependence of pelvic inclination (anteversion) on its skewing (lateral inclination to the kneeling lower limb).
B. The dependence of the angle a (of the body inclination toward the vertical z-axis) on skewing the axis of temporal bones against the horizontal xy-plane (lateral slant to the kneeling lower limb).

hips return to the neutral position and only then the body extension is completed. This monitoring complies with the above studies and the analysis of video records (see Figure 1). The angle α moves within the range of approx. 10–55°.

Furthermore, one can focus on the axial system rotation. In particular, one can monitor the dependence of the size of the angle included between the shoulders axis projection (acromion join) and the hips angle projection (trochanter join) to the horizontal *xy*-plane on individual stroke phases. Hereinafter this angle will be called the *shoulders-hips* angle. Results are indicated in the cyclogram in Figure 3B, where for the sake of better orientation the angle α, i.e. the body inclination to the vertical z-axis is construed as a dependent variable.

The neutral position of the canoeist, i.e. the beginning of the transmission phase can be taken as an initial point. At this point, the canoeist's body is straight, and the paddle is out of the water (see Figure 1A). It is obvious that the *shoulders-hips* angle is approx. 22° (see Fig. 3B). This angle is already given by the very geometry of the canoeist kneeling and the technique of C1 riding. The projection of the hips axis to the horizontal *xy*-plane is not absolutely perpendicular to the canoeing direction. Therefore, the hips joints axis is rotated by approx. 5° in the direction behind the kneeling lower limb. On the other hand, the axis of the shoulders is rotated by approx. 17° in the direction behind the supporting lower limb after pulling the paddle out of the water (see Fig. 3C). Therefore, the axial system lift in the neutral position is slightly rotated behind the supporting lower limb. During the transmission phase, the *shoulders-hips* angle of course increases. The total axial system turns over more behind the supporting lower limb until this angle reaches its maximum, i.e. 55°. Interestingly enough, even before the start of the catch phase, the angle again decreases, approx. by 10°. This shift is probably caused by kneeling on the edge of the pool with the counter-current. However, it should not occur at all if possible. Combining Figures 3A and 4A makes it clear that the position of hips and pelvis is generally unchanged in this part of the transmission phase of the stroke. Therefore, the change of the angle *shoulders-hips* has only been caused by the change of setting the position of the shoulders axis, which starts to return to the neutral position at this moment. Thus, the cyclogram on Figure 3B may serve as a partial descriptor of the stroke execution quality.

During the catch phase, when the centre of gravity of the upper half of the body is furthest forward, the canoeist must initiate the resistance force on the blade (in addition to its immersion) caused by the liquid flowing around its profile. As the liquid itself flows against the relative canoeist movement, this manoeuvre requires some time and change of the body position geometry. The cyclogram on Figure 3B proves that this happens by the change in setting the *shoulders-hips* angle as the angle α does not change almost at all at this phase of the stroke. With regard to the above analysis, this process is implemented by changing the position of the axis of shoulders.

It is followed by the pull phase where together with the decreasing angle α also the *shoulders-hips* angle decreases in the linear trend. Obviously, the axial system here is exposed to the load both in terms of the rotation and body extension. By the end of this phase the projection of the shoulders axis to the horizontal plane passes through the zero position, when it is vertical to the canoeing direction. The rotation of shoulders in the direction behind the kneeling lower limb stops and the exit phase begins. During this phase as well as in the immersion phase, the angle α remains almost unchanged. The body is already in the straightened position and the hips and pelvis skewing almost does not change at all (see Fig. 3A and 4A). The rotation of shoulders begins in the direction behind the supporting lower limb (see Fig. 1). Thus, the correction of the canoeing direction is almost certainly provided by the kinematic chain linked to the change in the position of the shoulders axis, i.e. to the rotation of the axial system towards the supporting lower limb. Note the interesting projection of the shoulders axis to the plane of the horizontal *xy*-plane and the vertical *yz*-plane. The cyclogram on Figure 3C confirms that in no stroke phase shoulders as well as hips (Fig. 3A) and pelvis (Fig. 4A) are parallel with the horizontal plane.

Below we will focus on the rotation and the lateral skewing of main segments of the axial system (head, chest, pelvis) during the stroke. In Fig. 4A, see the cyclogram depicting the anteversion and skewing (lateral bend in direction to the kneeling lower limb) during individual stroke phases. It is obvious that this dependence is almost linear, whereas the more the centre of gravity of the body moves forward behind the supporting leg during the stroke, the farther the pelvis is located from its neutral position.

For the position of the head during the stroke, see the Fig. 4B. The cyclogram depicts the dependence of the body inclination α on skewing the axis of temporal bones to the horizontal *xy*-plane. From this image, it is clear that in stroke phases, which are close to the neutral position of the canoeist, the head is slightly bent to the side of the supporting lower limb (skewing shows slightly negative values). This position is the result of compensation movements of the head in relation to skewing the pelvis and forces generated on the paddle during the stroke and when exiting from water. On the other hand, in stroke phases, when the body inclination approaches its maximum, the head shows a rotational movement towards the upper limb on the side of the supporting lower limb. This position helps the canoeist reaching with his paddle as far forward as possible.

Considering changes of the positions of the pelvis, shoulders and head during paddling, we can easily notice that the whole axial system will be exposed to laterally asymmetric loads. Movements of the chest and its relative position to other segments of the postural system will then be determined by the geometry of the compensatory movements performed by the body as a whole. Depending on the individual stroke phases, it will therefore be a lateral body bending towards the cranial lower limb associated with its rotation around the cranio-caudal axis. We can state that all observations qualitatively match the video-analysis of real strokes of the control canoeists canoeing.

Asymmetric hypertrophy of m. iliopsoas and m. quadratus lumborum

It is a good idea to check at the level of individual muscles whether canoeists with a long loading history manifest unilateral overload in asymmetric muscle hypertrophy. For this purpose, cross sections of m. iliopsoas and m. quadratus lumborum on the kneeling and supporting side of the body were compared in individuals (N = 5) selected from the experimental group of subjects.

Results of the implemented investigation have been processed in Table 2. It shows that with all subjects cross sections of m. quadratus lumborum and m. iliopsoas on the side of the kneeling leg (paddling side) are smaller than on the side of the supporting leg. These differences average to 18% with m. guadratus lumborum and 11% with m. iliopsoas. Approximately, the same results can be seen with the median.

Figure 5 was created for the purpose of generalising conclusions. Here, the very shapes of depicted box-plot charts indicate abnormal distribution of cross sections of monitored muscles. Furthermore, the normality tests confirmed the need of using non-parametrical statistics. According to them at the statistical significance level α= 0.05, the data normality is disrupted with m. quadratus lumborum on the side of the kneeling leg and with m. iliopsoas on the side of the supporting leg, i.e. in 50% cases. Taking into account the low number of subjects in the selection file (N=5), this result is quite understandable.

Tab. 2. Estimate of the stroke proportionality with the paddling frequency of 27/min. (N = 9, α = 0.05).

Subject No.	Kneeling lower limb cross section		Supporting lower limb cross section		Cross section difference		Age
	MQL (cm^2)	MI (cm^2)	MQL (cm^2)	MI (cm^2)	D MQL (%)	D MI (%)	(years)
1	6.6	16.9	10.1	17.5	35	3	48
2	9.1	23.1	9.7	23.6	6	2	42
3	6.2	12.6	8.6	16.6	28	24	40
4	5.8	27.5	6.0	31.4	3	12	27
5	6.4	18.9	7.6	21.6	16	13	43
Average	6.8	19.8	8.4	22.1	18	11	40
SD	1.3	5.7	1.7	5.9	14	9	8
Median	6.4	18.9	8.6	21.6	16	12	42
IQR	0.4	6.2	2.1	6.1	22	9	3
Min	5.8	12.6	6.0	16.6	3	2	27
Max	9.1	27.5	10.1	31.4	35	24	48

Legend: MQL – m. quadratus lumborum; MI – m. iliopsoas; DK – lower limb; SD – standard deviation IQR – interquartile range.

The results show that the population of long-term training canoeists on the C1 suffer from the unilateral hypertrophy of m. quadratus lumborum and m. iliopsoas. This observation was statistically verified with the result that the difference in cross sections of both monitored muscles is significant in pairwise comparison at the standard level of statistical significance α = 0.05 (p-value = 0.043 for both tests).

On the basis of findings, we can assume that regular training efforts associated with flatwater canoeing can contribute to the asymmetric size of the cross sections of m. iliopsoas and m. quadratus lumborum. With both muscles, larger cross sections and therefore also the general strength on the side of supporting lower limb can be expected.

DISCUSSION AND PRACTICAL APPLICATIONS

The above analyses indicate that riding the C1 flatwater canoe results in the asymmetric load of the postural system in terms of geometry. In terms of individual muscles, this asymmetry can be related to the stroke phases. As individual phases last for various periods of times and the canoeist's body is in various geometries, this loading is specific both in terms of volume and intensity of muscle and muscle group involvement. Based on the knowledge of the functional anatomy, it is possible to create a general picture of the kinesiological aspects of paddling on the C1 speed canoe using video analyses and data from 3D kinematic analysis.

Catch phase

During the phase of immersing the paddle into the water, the entire axial system is rotated along the cranio-caudal axis in the forward direction behind the shoulder girdle on the kneeling lower limb side. Furthermore, the flexion and bend of the body above the kneeling lower limb and compensatory bend of the head in the opposite direction occur. In the pelvic area, a short-term rotation occurs again along the cranio-caudal axis, forward behind the spina iliaca ant. sup. on the kneeling side of the lower limb. Furthermore, the pelvis is ejected to the side of the supporting lower limb, which is associated with the pelvis skewing down on the paddling side. The body weight is transferred to the supporting lower limb (Fig. 1B1 and 2).

From the muscular point of view, due to the pelvic deflection, m. quadratus lumborum is more loaded, bilaterally, with the predominance of it on the side of the supporting lower limb. This activity is compensated by the opposite stabilisation of the abdominal muscles, which are therefore also exposed to an increased load. Furthermore, both paravertebral spine straighteners, in particular Th/L and L/S of the transition, a group of abductors of the hip joint on the side of the supporting lower limb (in particular m. gluteus medius and m. minimus, the piriformis muscle and the tensor fascia latae muscle) are involved. Furthermore, m. iliopsoas is subject to increased load, again bilaterally with the superiority of the one on the side of the supporting lower limb. This muscle action contributes to maintaining balance of the supporting lower limb to a great extent in the same way as a stabiliser of the knee joint, in particular quadriceps femoris.

Stroke phase

In the beginning of the stroke phase, the body is in significant flexion, in particular its upper part, when the thoracic part of the spine passes into a kyphotic position (hunchback). Due to the powerful stroke of the paddle (against the water resistance), the asymmetric

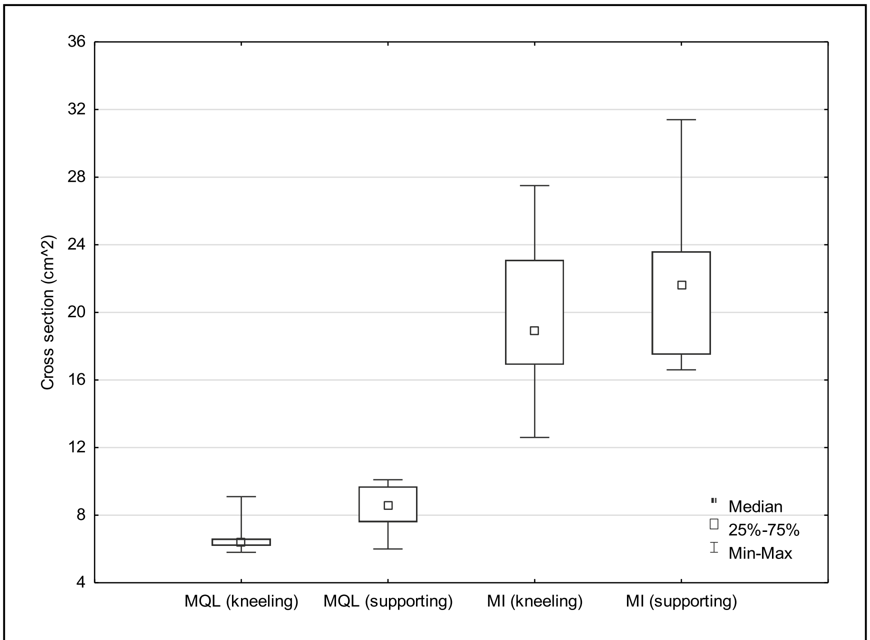

Fig. 5. Graphical comparison of MQL and MI cross sections on the kneeling side and the supporting side of the lower limb.
Legend: MQL – m. quadratus lumborum; MI – m. iliopsoas.

position of the body increases. Its lateral bend on the paddling side occurs. The entire axial system is rotated along the cranio-caudal axis in the backward direction behind the shoulder girdle on the kneeling lower limb side.

During the paddle stroke along the boat, the canoeist gradually transfers the weight to the kneeling lower limb (Fig. 2). At the same time, the side view (Fig. $1C_1$) clearly indicates that the body is straightening. The angle α is gradually decreasing. On the other hand, the bend of the body to the paddling side deepens as well as the compensation bend of the head in the opposite direction (Fig. $1C_2$ and 4B). This body position contracts sharply with the neutral posture (compare, Fig. 1 A and C). These two images indicate very well the lateral asymmetry of the whole movement as well as the body forward bend at the neutral pelvis position.

The pelvis movement intensifies to a lateral deflection to the side of the supporting lower limb and slopes down to the side of the paddling, which is obvious on Fig. $1C_2$. As data from the 3D kinematic analysis confirm, the angle β_c is larger in comparison with the angle β_a. This difference is in particular caused by the fact that during this phase the centre of gravity of the canoeists goes beyond the vertical axis of the boat. The rotating effect of the gravitation force F_g must be compensated by the effect of the horizontal force F_h. With completing stroke phase, the whole pelvis returns back to the neutral position.

Due to the force stroke the ventral group of the body muscles is loaded (strengthened) on the side of the kneeling lower limb. On the same side also m. quadriceps femoris, hip joint adductors, m. iliopsoas and m. obliquus abdominis externus are subject to higher load. On the side of the supporting lower limb m. quadratus lumborum, spine straighteners Th/L and L/S of the transition and also m. obliquus abdominis internus are loaded.

Exit phase

In the beginning of the phase of paddle exiting from the water, the power phase of the stroke is completed, and the body gets gradually straightened releasing the previous significant tension. The different position of the shoulders is manifested by the lateral inclination of the upper part of the body to the paddling side and the compensatory inclination of the head to the opposite side. The pelvis remains in its lateral deviation on the side of the supporting lower limb and in the backward rotation behind the spina iliaca ant. sup. on the paddling side. In this way, the movement of arms and the upper part of the body is compensated. The body weight remains more on the kneeling lower limb. Figure $1D_1$ clearly shows the angle α_d, which represents the body deviation from the neutral position. The aim is that, by the end of the pulling phase, this angle is 0°. As in the side views A_1 and C_1, the position of trochanter major femoris on the kneeling side of the lower limb is also in the neutral position in this stroke phase.

The above position is compensated, and it leads to a greater load, in particular of the knee stabilisers (mainly quadriceps femoris), hip adductors, iliopsoas and quadratus lumborum on the side of the kneeling lower limb. On the same side, m. pectoralis major is also loaded. On the part of the supporting lower limb m. trapezius (in particular upper fibres) and straighteners of the Th/L i L/S area are loaded.

Transmission phase

In the transmission phase, the weight is gradually transmitted from the kneeling lower limb to the supporting lower limb. The centre of mass of the body is directed to the forward movement. The position of the supporting lower limb slightly lateralises (deviates) the pelvis and slopes it down to its side. The rotation of the pelvis is temporarily balanced to a neutral position (Fig. $1A_1$). At this phase of the stroke, the paddle is not supported by water. So to maintain balance, it is very important that the gravitational force Fg passes along the vertical axis of the boat.

The mentioned pelvic inclination (see Fig. 3A) proves that the very kneeling on the C1 creates a geometrically asymmetric postural muscle involvement. On the side of the supporting lower limb, it is in particular the case of m. quadratus lumborum and flexora of the hip joint, in particular m. iliopsoas. Also spine straighteners in the lumbar area (mm. erectores spinae) are loaded.

CONCLUSION

On the basis of the findings, we can assume that during, the flatwater canoeing, the postural system is exposed to two types of asymmetric loads. Both are related to the movement geometry. In the first place, it is a lateral asymmetry, which is based on the very nature of the one-sided paddling on this type of vessel. Another asymmetry is connected to the forward-backward body movement and its time-dependent deflection from the neutral posture. With the kneeling knee and the foot of the supporting lower limb fixed to the boat, the body together with the head and upper limbs perform movements in a relatively wide range. Therefore, there is a significant disproportion here between fixation movements of the lower part and phase movements of the upper part of the body.

When canoeing on the C1, a significant unilateral overloading occurs with m. quadratus lumborum on the part of the supporting lower limb (side without paddle). Furthermore, spine straighteners in the lumbar area are overloaded, in particular in the part of the supporting lower limb. Last but not least however, the bilateral asymmetric overloading of m. iliopsoas occurs. The asymmetrical position of the lower limbs itself and holding the paddle on one side of the boat results in instability, which the canoeist must compensate by shifting the centre of gravity of the body higher above the kneeling lower limb. This position is achieved by the so-called pelvic lateralisation from the paddling side and by its skewing to the kneeling lower limb.

Furthermore, one can assume that during a longitudinal training effort the lateral disproportion in the volume and intensity of postural system loading is the cause of different cross sections of iliopsoas muscle and quadratus lumborum muscle on the side of the kneeling and supporting lower limbs. With both muscles, larger cross sections on the statistical significance level $\alpha = 0.05$ and therefore also strength on the side of supporting lower limb can be expected. Mentioned findings are in compliance with the kinesiological analysis. Therefore, we can assume that this is a result of the side disproportion in terms of volume and intensity of the postural system load. With m. iliopsoas it is also affected by the fact that it is loaded in various isometries.

The above findings are important for planning compensation processes within the regeneration, reconditioning or rehabilitation phases of the training. In particular, this is a targeted physiotherapeutic intervention or structuring compensation exercises and movement activities.

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