INVITED REVIEW

TRENDS in
Sport Sciences
2015; 2(22): 61-69
ISSN 2299-9590

Biomechanical characteristics of rowing

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Abstract

Competitive rowing demands long-term, unilateral and non-physiological training. This discipline requires not only technical preparation, but also strength and endurance training, which is largely conducive to the occurrence of micro-traumas that can cumulate and lead to a spectrum of overloading changes in the motor organs, particularly in the lumbar spine. The factor most conducive to the occurrence of pathological changes in the spine is the rowing cycle, both on water and on ergometer, wherein the athlete performs multiple repetitions of maximum flexion and extension in the sagittal plane of the lumbar spine. Of note is the fact that during a single, 90-minute training session the rower engages over 70% of his or her overall muscle mass, performing 1800 cycles of flexion and extension. These motions performed with oars as additional weights lead to the overloading of both the active and the passive spine stabilization system. Moreover, the system is impacted by compression forces in excess of 6000 N that can lead to destruction of the motor system.
It is therefore necessary to understand the biomechanics of spine movements and to perform the biomechanical analysis of rowing, as well as use conclusions from the analysis in the training process in order to counteract overloading changes in the motor system, particularly the spine.

KEYWORDS: lumbar spine, mechanical overload, compression forces.

Received: 7 December 2014
Accepted: 26 February 2015

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What is already known on this topic?
Rowing is a sport that strongly affects the lumbar spine. To protect the spine from overuse diseases the biomechanics of rowing must be described and understood. A great many studies on the topic have been published over the years.

The highest-level success in rowing is usually achieved relatively late [1]. The median age of Olympic or world championship rowers increases systematically. This phenomenon can be illustrated by the achievements of Vaclav Chalupka, Matthew Pincent – the most prominent athletes in recent years – Tomasz Kucharski, Robert Sycz, Marek Kolbowicz, or the five-time Olympic medal winner Steven Redgrave. These rowers won their respective medals in the most important sporting events before the age of 30. However, success in this discipline requires rational training from the earliest age [1, 2].
Covering the classic distance of 2000 m (lasting between 5 and 8 minutes depending on the event, sex and atmospheric conditions) requires over 200 full rowing cycles. Rowing engages over 70% of muscle mass and requires correct endurance and strength preparation, as well as attainment of very high efficiency parameters. Rowers need plenty of muscle strength in order to achieve shell velocity at the start, and high oxygen efficiency to maintain that velocity while covering the distance on the regatta course during an event [3, 4].
Results in rowing depend on multiple factors, the most important of which are [2, 5, 6]: athletes' somatic

makeup, their output potential, level of technical, tactical and psychological preparation, nutrition, technological progress in the construction of shells and oars, atmospheric conditions, and training process optimization.

According to Henning [1], apart from efficiency predispositions, athletes should also possess proper somatic parameters, i.e. long upper and lower limbs and appropriately long trunks in order for the oars to stroke in the optimal angle range.

Freedom of oar operation also depends on flexibility, where joint mobility utilized in the biomechanical system of the rowing cycle is one of key contributing factors [2]. The flexibility level, though discarded in the past, has in recent years consistently been considered an important element of a rower's ability.

The angle of mobility in the hip, shoulder and ankle joints as well as in the shoulder girdle determines the efficiency of boat propulsion. The range of flexibility in these joints affects the freedom of movement in the optimal angle range of oar strokes. However, the aforementioned factors connected with the notion of flexibility must be supplemented with elements affecting its development [7] such as:

- ligament and muscle flexibility
- the athlete's age and gender
- body temperature and the temperature of particular muscles
- time of day and temperature in training location
- muscle strength
- fatigue and emotional state.

Apart from flexibility and endurance that should characterize all rowers, an indispensable motor skill is the level of developed muscle strength. Due to a large number of repetitions of strokes, this action should be undertaken with the highest possible output of internal strength in every drive. According to Henning [2], the development of muscle strength should progress in a fashion not increasing the weight of the athlete that must be propelled along with the shell itself. This is directly connected to the impact of increased mass (and therefore weight) on the amount of additional work performed in a unit of time by the (internal) muscle strength of the athletes forced to counteract increased resistance forces (as the shell's immersion increases). Modern rowers are, therefore, tall and very slender individuals. Studies by Garay et al. [5] and Piotrowski et al. [8] indicate that, in comparison with physically inactive persons, rowers can be distinguished not only by their height and weight, but also the length of upper and lower limbs (especially shanks), the breadth of shoulders, the breadth of distal bases of the upper and lower limbs, large muscle circumferences, particularly in the forearm, as well as correct proportions between tissue components.

According to Henning [2], the amount of strength expended in rowing is the ability to overpower resistance forces that occur during oar strokes or to counteract them at the cost of muscle exertion. The dominant role of various functional muscle groups during different phases of rowing should be stressed [9]. The following muscle groups dominate during the catch phase (Figure 1):

A. deltoid, tricpes brachii, trapezius, serratus anterior, erector spinae, rectus abdominis, gastrocnemius, tibialis anterior, hamstrings.
B. deltoid, trapezius, teres major, erector spinae, serratus anterior, quadriceps, gluteus maximus, gastrocnemius, soleus, hamstrings.

The following muscles perform the majority of the work in the pulling phase (Figure 2):

A. deltoid, biceps brachii, brachioradialis, erector spinae, quadricpes, gluteus maximus, gastrocnemius, soleus, hamstrings.
B. traoezius, biceps brachii, posterior deltoid, teres minor, brachialis, bracioradialis, extensor carpi ulnaris, flexor carpi ulnaris, latissimus dorsi, pectoralis major, quadriceps.

Similar muscles in different angle configurations dominate the drive phase (Figure 3):

A. trapezius, posterior deltoid, brachialis, biceps brachii, brachioradialis, latissimus dorsi, forearm extensors, gluteus maximus, quadriceps.
B. trapezius, anterior part of deltoid, triceps brachii, wrist extensors, gastrocnemius, rectus abdominis, hamstrings.

In order to achieve the top results in rowing, athletes must take part in a very strenuous training process that can be divided into two parts [1, 2]: preparation on land (general development, strength and endurance training) and specialized training (ergometer or indoor rowing tank).

It is stressed that the more experienced athletes become, the more effort must be devoted to specialized training, i.e. work focused on rowing, while younger athletes should concentrate on general development preparations. Time of the year also affects the range and character of exercise loads in rowing. The winter season is mostly

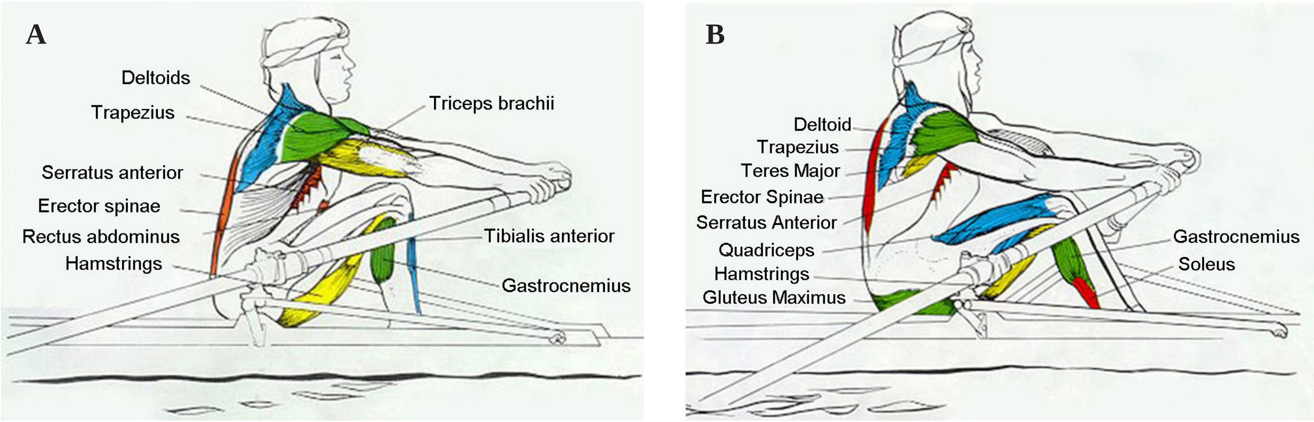

Figure 1. Dominating muscles during the catch phase [9]

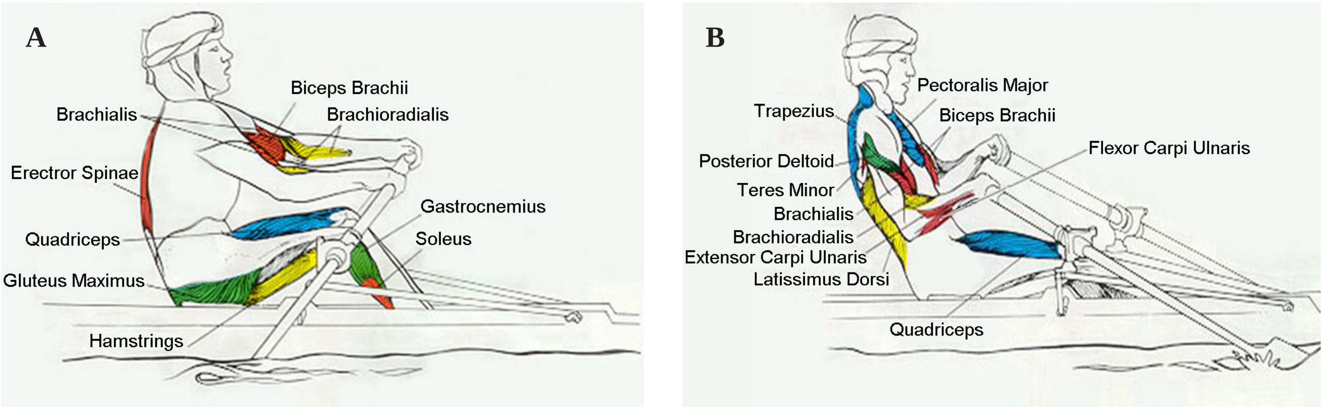

Figure 2. Dominating muscles during the pulling phase [9]

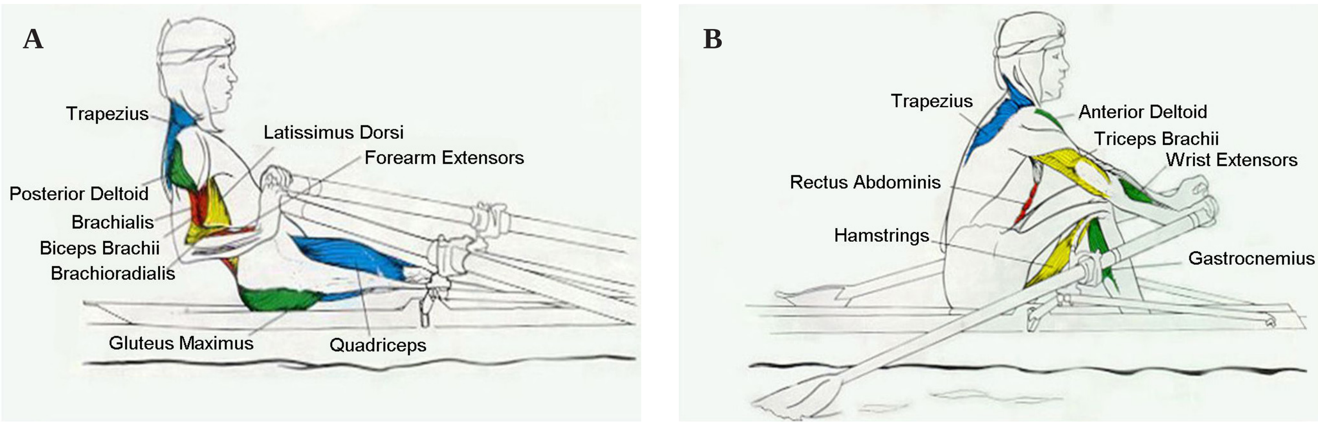

Figure 3. Dominating muscles during the drive phase [9]

spent on running, skiing, swimming and strength building exercises (particularly, strength endurance). Depending on training levels, athletes then engage in exercises that approximate rowing with the use of ergometers or indoor rowing tanks [10].

According to Henning et al. [1], the training objective for prospective rowers should be attaining an appropriate level of flexibility, strength, endurance, balance and speed. Attaining the correct level of joint mobility facilitates mastering rowing technique and provides better conditions for endurance and strength development and decreases the risk of injury. Traditionally performed stretching exercises where joints are passively set in the angle range that causes the sensation of stretching (with additional, rhythmic pushes) are insufficient in their efficiency due to stretch reflex – a defensive mechanism protecting against muscle rupture that can lead to microtraumas in muscle fibres. It is possible to bypass the stretch reflex through post-isometric relaxation, based on feedback between muscle spindles (contraction strength receptor) and the Golgi apparatus (stretch receptor). In order to perform muscle stretching using post-isometric relaxation the athlete should: adopt a stable position, perform a passive motion in the joint to preliminarily stretch the muscle, isometrically extend the stretched muscle for less than 20 seconds, relax the muscle and deepen the range of mobility in the joint. This sequence is repeated multiple times and the purpose of the exercise is to attain full range of mobility in the joint. In order for the stretching to be efficient, all muscle functions must be considered in all the joints it passes, e.g. the rectus femoris muscle should not only be stretched through flexion of the knee joint since it also functions as the flexor of the hip joint and, with the lower limb stabilized, causes anteflexion of the pelvis. Therefore, when the rectus femoris muscle is stretched, the hip joint should be set and stabilized in the extended position with the pelvis in retroflexion [11].

Strength training in rowing encompasses all four of its aspects: strength endurance, general strength, power and maximum strength. Concerning spinal injuries, particular attention is paid to the notion of so-called "rower's strength endurance", which is a type of endurance capability. It is the ability to overpower resistance forces in long term by the muscles taking active part in rowing [12, 13]. Strength is usually trained during so-called strength exercises, where different muscle groups work in a strict sequence at specially prepared stations.

Due to the importance of the fitness of the lumbosacral spine to the biomechanical conditions of the rowing cycle, particular care must be taken to protect this part of the body. Even lifting small weights causes huge overloading, in particular in the L5 vertebra area. According to many authors [14-17], most strength exercises used as part of rowers' training, in particular those that strengthen dorsal and abdominal muscles, carry a threat of overloading the lumbar spine. Different types of trunk extensions from forward bend position with additional weights placed on the back are considered highly dangerous. These weights should be held close to the chest in a way enabling the athlete to release them at any time [18]. This also pertains to the angle range of the exercise – it should be performed without overextending. Any overextension additionally overloads intervertebral discs in the lumbosacral spine. Exercises aimed at strengthening abdominal muscles are similar – during forward bends from the recumbent position weights should not be held on the stomach or the chest, but should be held close to the back to maintain the ability to safely drop them at any time, in spite of the fact that the weight operates on the longest arm in relation to the axis of rotation located in the lumbosacral spine [18].

Where leg press is often used for exercise, the reverse variant is recommended, i.e. where the athlete presses away from the ground with the weight rather than pressing the weight upwards. The latter variant may lead to circulation problems, with the lower extremities experiencing ischemia, while blood flow and pressure in the head increase.

Yet another type of strength exercises used by rowers are activities mimicking rowing motions in water, in the rowing tank, and on ergometers. Many authors [15, 17, 19-23] prove it to be a type of exertion that particularly overloads the lumbar spine. Schultz [24] studied overloading of the L3-L4 motion segment, concluding that median compression force in this area is 3919 N in males and 3330 N in females. Maximum force value occurred at the end of the drive phase and was noted as 6066 ± 186 N in males and 5031 ± 694 N in females. According to White and Panjabi [25], as well as Ogurkowska [26, 27], compression force of such extent can destroy the motion segment of the spine.

The data presented above indicate that overloading of the lumbar spine occurring among rowers during strength training carry a high risk of overload-caused pain in the L1-L5 segments.

The lumbosacral joint has 4 degrees of mobility [28]. Mobility of the joint is complex, since rotation by about 3 degrees and displacement by up to 2 mm in three directions [29] can occur simultaneously. Mobility occurring in the joints between articular processes is of a rolling character [30]. When the joint is flexed, the inferior articular process above moves to the right and up along the superior process of the vertebra below, and down and towards the back during extension. The total range of displacement is between 5 and 7 mm. According to Bull and McGregor [31], the rowing technique, apart from flexion and extension, also requires axial rotation of the trunk. Compression forces additionally occur among rowers along with the highly pathogenic ante-retro shearing forces that occur during transmission of weight from trunk to lower limbs and during actions performed by the upper limbs.

Incorrect position during catch and drive is often the reason for sudden pain affecting the lumbosacral region. It is therefore important to teach all rowers how to maintain a safe position. Spine flexion is eccentrically controlled by contractions of spinal extensors. When the trunk is bent at a 45° angle, the rear ligament system, along with the thoracolumbar fascia, are flexed and the spinal extensors cease to contract [32]. When the spine no longer experiences additional loads, the sequence of forward flexion may be altered, e.g. anteflexion of the pelvis in the sagittal plane can occur before flexion of the spine. In this case constant isometric contraction of the thoracolumbar extensors is required that greatly exceeds the range of 45° anteflexion in the trunk, since the rear ligament system remains limp, and therefore does not support weight shifts. This motion template can be described as typical for anteflexion among dancers.

However, if additional weight is added, e.g. in the form of oars in the drive phase, this altered motion template becomes disadvantageous since muscles are then forced to perform actions they do not support [33]. When weightlifting strategy is altered from ligament to muscle-focused, compression increases along with angles of flexion. According to Gracovetsky [33] and Farfan [32], using ligaments whenever possible is ideal. Ogurkowska [26, 27] and Reid and McNair [34] conclude that the extent of flexion in the lumbar segment that occurs during a rowing drive can increase the occurrence of trauma in the lumbosacral segment. The above conclusion is also confirmed by results of studies by Adams and Dolan [35-37], as well as Cyron and Hutton [38] performed on section material. The researchers concluded that overflexion of the lumbar spine can fracture the ligament structure and, in combination with compression force, may cause damage to intervertebral discs. This fact may refer only to kinematics of the trunk or lumbar spine during the drive phase. Hosea et al. [16], for example, concluded that the trunk moved by 30° of flexion in the beginning of the drive phase (while the feather of the oar is submerged) to 28° of extension at the end of the phase. In 2000, Bull and McGregor [31] used electromagnetic sensors placed on the sacrum as well as the thoracolumbar junction in order to assess its movement during ergometer rowing. The authors concluded that at the start of the drive the sacrum was in a position similar to upright extension in the sitting position and that its rotation by 30° to 40° commences at that moment. The thoracolumbar junction is characterized by its 20° to 25° flexion at the start of the drive phase. This value was recorded in upright extension in the sitting position. Subsequently, during the drive phase about 60° of forward bending in this section was recorded.

Bull and McGregor [31] stated that in order to assess potential threats the extent of flexion in the lumbar spine was necessary, particularly its relation with the individual scale of mobility in this segment of the spine. A similar notion was studied by Caldwell and McNair [39]. The purpose of their work was to examine changes in the angle of inclination of the lumbar spine along with the level of muscle activity in selected spinal extensors during rowing attempts. Changes in inclination of the lumbar spine and muscle activity in the drive phase during ergometer exercises were recorded. The inclination of the lumbar spine was recorded with a digital camera and assessed via computer motion analysis and surface markers affixed to L1-S1 spinous processes. The total range of flexion in the lumbar segment of the spine for each case was ascertained with the use of a method described by Dolan and Adams [40]. The angle of flexion in the lumbar segment was recorded in standing, relaxed position and then subtracted from the angle of flexion in forward bend position (fingers touching feet). Next, movements of the spine during rowing were analysed and expressed in flexion percentages:

$$\text{flexion } \% = (\theta_W - \theta_{ST}) / (\theta_L - \theta_{ST}) \cdot 100$$

where:

θ_W – angle of flexion in the lumbar spine while rowing,
θ_{ST} – angle of flexion in the lumbar spine while standing,
θ_L – angle of flexion in the lumbar spine with fingers touching feet.

To ascertain the extent of activity in three spinal extensors, Caldwell and McNair [39] utilized the surface EMG technique. The middle frequency of the EMG signal monitored muscle fatigue in spinal erectors during regular maximum exertion of active muscles, both before and after a rowing try. EMG activity was recorded in areas of lumbar multifidus, iliocostalis as well as the longissimus thoracis. A relation was sought between EMG signal strength of the aforementioned muscles and the moment of measurement during the drive phase. The above relations were examined in three time periods of the try (distance of 2000 m, 20%, 60%, 95% of race time). The authors concluded that lumbar multifidus muscles increased their EMG activity until half drive time with a slight (50-70%) change in activity observed afterwards. In the final phase it was ascertained that the measured parameters were unequivocally decreased to their starting value (beginning of drive phase). The above conclusions were formulated for three time periods of the race with the highest multifidus activity recorded respectively at the moments before the end of the race.

Longissimus thoracii is characterized by a high increase in activity until the middle of the drive phase with an equally fast decrease to a value comparable with starting value. Comparing the EMG results for this muscle for the separate time periods of the race (20%, 60%, 95%) results in an unequivocal increase in its activity along with rowing time.

Iliocostalis activity during rowing was very similar to lumbar multifidus activity.

Caldwell and McNair [39] also ascertained that rowers achieved a relatively high range of flexion in the lumbar spine during drive which increased throughout the try. This indirectly indicates that the apparent fatigue of spinal erector muscles may partially be responsible for the observed increase in flexion in the lumbar spine (20%, 60%, 95% of the try). All relationships observed in the paper in question were statistically significant, with a significance ratio of $p < 0.05$.

According to Lamb [41], fatigue of spinal erector muscles is a factor causing the increase flexion in the lumbar spine. The main forces increasing the speed of the shell are generated by the athlete's limbs. In turn, spinal erector muscles play an important role not only in generating strength to increase the shell's speed, but also in regulating the extent of flexion and stretching of the lumbar spine. Flexion control practiced by rowers prevents muscle fatigue, especially during the catch phase.

Many other authors also quantitatively expressed the flexion in the lumbar spine or studied the role of dorsal muscles during the drive phase of rowing. Caldwell and McNair [39] found that among rowers under study the mean total deviation of the lumbar spine from the vertical position to full flexion was 52.5°. This value was slightly lower than indicated in by Dolan and Adams [40] i.e., 55-56°.

It was also demonstrated that the resultant moment of force flexing the lumbar spine segment increases dramatically in an individual depending on the incline of the segment from the vertical position. Spinal structure strain also increases. According to Dolan and Adams [40], rowers with relatively low total range of mobility may develop limited flexibility of soft tissues (i.e. intervertebral discs and ligaments) and experience progressive traumatic changes.

Adams and Dolan [35] demonstrated the impact of the percentage of flexion angle in the lumbar spine on the strain occurring in intervertebral disc during the drive phase. During the first 50-60% of the phase's duration spinal flexion is observed in the L1-L5 segment, which represents 74-89% of total value.

Caldwell and McNair [39] also found an increase in the flexion during the rowing cycle, from 75 to 90% of total motion range. This data was compared with results from Bull and McGregor [31], who recorded an increase in the lumbosacral and thoracolumbar angles after 10 minutes of the stress test.

Many authors claim that the flexion in lumbar spine in rowing can be compared with repeated action of picking objects up from the floor. An increase in the flexion of the lumbar segment to a value corresponding to 67-73% according to Sparto et al. [42] and 83-90% according to Dolan and Adams [40] of the maximum flexion was achieved during the lifting test.

It is also worth noting that the value of the lumbar spine bend strongly impacts potential overloading since the flexion of the spine in the sagittal plane is connected with the elimination of lumbar lordosis and the closing of intervertebral spaces. This in turn is connected with the compression of intervertebral discs and the stretching of rear ligament structures. The nucleus pulposus is then displaced towards the rear, near the spinal canal and the deviation of the trunk from the vertical position simultaneously exacerbates the stress resulting from the increase of the moment of force. Maximum flexion occurs during the catch phase of the rowing cycle. The drive phase commences and water resistance increases. External stress on the spine increases dramatically and is a sum of moments of force on the oarlocks and weight forces in the trunk. Rhythmic repetitions of these stresses lead to fatigue accumulation.

The spinal erector muscle limits the range of flexion mobility to the front and back, thereby contributing to protecting the intervertebral disc and ligament structure. However, the compression force along with the flexion in the lumbar spine may particularly affect the intervertebral disc. In rowing, the resultant of these values is significant. Hosea et al. [16] found that the maximum value of compression force exceeds 5000 N in females and 6000 N in males, while its mean value is in the range of 3000-4000 N (drive phase). The likelihood of trauma occurring naturally increases along with the number of repetitions in a rowing try.

According to Callaghan and McGill [43], cyclically repeated extending and flexing movements in connection with the relatively low compression force nearly always leads to disc herniation. The authors also stress the fact that even during a single 90-minute training session the athlete performs around 1800 lumbar spine flexion and extension cycles, generating forces that are the likely cause of trauma. Caldwell and McNair [39] attempted to answer the question: How to avoid spine trauma in rowing?

From the perspective of technique development, if a rower increases the range of forward pelvic bend in the sagittal plane during the start of the drive phase (when the flexion in the lumbar spine is the most extreme), the required flexion in the L1-S1 segments should decrease. Therefore, stresses in spinal structures also decrease. Dolan and Adams [40] seem to confirm that suggestion stating that during the action of lifting an object from the floor, which requires more pronounced flexing in the hip, lesser flexion stress values in lumbar spine tissues are observed.

From the perspective of training rules, the conclusions presented above indicate that the abilities of lumbar spine erectors that control its flexion within its physiological endurance should not be overlooked. The above statement was presented based on a study on muscle activity and lumbar spine flexion during a try on an ergometer in accordance with Caldwell and McNair [39]. Similar studies were also performed by Bull and McGregor [31]. Even though the ergometer physiological test is similar to rowing on water, they do not bear direct comparison. On the ergometer the rowing motion is performed in a 2D plane, while rowing on water requires axial rotation of the trunk, a movement that cannot be simulated on an indoor machine. The impact of axial rotation can cause damage to spine tissues, as confirmed by Adams and Dolan [36]. The authors note that adding this type of movement along with flexion and slight compression force can cause much larger stress to articular capsule and ligaments.

Hase et al. [44] also performed a number of studies pertaining to the negative impact of ergometer rowing on lumbar spine overloading. A group of competitive rowers and recreational rowers was studied. The resulting data allowed the assessment of potential trauma risk during rowing. The authors performed an experiment to determine kinematic values, external forces and EMG data during ergometer rowing. The acquired parameters were then supplemented into a full body musculature 3D model, which served as a basis for the assessment of forces and moments of forces in joints, muscle strength as well as contiguous strength in the joints. Hase et al. stressed the fact that stress models created for competitive and amateur rowers are very similar, with one notable difference in limb and trunk usage during rowing. Competitive rowers on average used more upper and lower limb force on ergometer hafts than amateurs, with a significant difference between the two groups in maximum ante-retro foot reaction force. These results suggest that both competitive and non-competitive rowers can be kinetically and kinematically modeled similarly during ergometer rowing, but certain significant differences in their usage of limbs and trunk must be taken into account. Competitive rowers utilize more quadriceps strength during the drive phase, and extend their knees more and their trunks less than the amateurs. For that reason competitive rowers develop more contiguous strength in their knees and require a higher flexing moment in the lumbar spine as well as knee-flexing moment to slowly complete the drive phase, before the change in direction and return phase. These studies resulted in the relation of maximum total forces to maximum spinal erector strength being recorded as 1.52 for competitive athletes and 1.18 for recreational rowers.

In light of data collected above from an analysis of internationally published rowing papers, results presented earlier by Ogurkowska [26, 27] on pathobiomechanics of trauma occurring in the lumbar spine among athletes are also interesting. The author indicates that the direct cause of repeat ailments in the lumbar spine in the group of athletes in question is spinal strain. In this case the essence of the strain is the gradual, multi-stage, excessive and accelerated wear of spine segments resulting from overloads exceeding its endurance.

The aforementioned spinal overloads most likely result from:

- certain aforementioned habitual methods of indoor training that utilize strength exercises, in particular those aimed at strengthening dorsal and abdominal muscles;
- indoor and outdoor rowing technique with repeated flexion and extension in the lumbar segment of the spine.

Stress and damage can affect any structure and tissue in the spine, but individual differences exist that lead to overtaxing and damage to spinal structures. Ogurkowska has proven that rowers most often suffer from the mechanism known as chronic overuse. The resulting stress changes affect spine-supporting muscles first and passive, vertebrae-stabilizing soft tissue next. The disorder impacts the activity of the former first, leading to the occurrence of notable degenerative and deforming changes.

Conclusions

Rowing as a competitive sport requires long-term, unilateral and non-physiological training, leading to stress and overloading that negatively affect the spine. Intensive overuse of the spine cannot be avoided in either general or specialized training.

Spine overloading usually affects athletes as a result of lack of consideration for adaptive and compensative abilities of the locomotor organs (with the body often still in active development) and, more importantly, as a result of developmental spinal disorders being overlooked in qualifying medical examinations.

What this study adds?

This is a complete review of available literature on rowing biomechanics. It is useful for coaches to develop proper training programs, as well for doctors and physiotherapists to protect the lumbar spine or to manage overuse changes.

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