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BIOMECHANICAL PRINCIPLES OF SPORTSWEAR DESIGN FOR KAYAK SLALOM ATHLETES

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Abstract: This article analyzes the biomechanical characteristics of double-bladed paddling in kayak slalom and defines the theoretical requirements for sportswear design adapted to these movements. The study is based on a theoretical biomechanical approach and examines the main paddling phases (Catch, Power, Exit, and Transition), body rotational movements, and functional muscle activity. Based on the analysis, requirements for zonal garment construction, elasticity, muscle stabilization, and thermal regulation are substantiated. The results provide a scientific theoretical basis for the future development of specialized sportswear models for kayak slalom athletes and subsequent experimental validation.

Keywords: kayak slalom, biomechanics, paddling, sportswear design, muscle activity, ergonomics.

Introduction. In recent years, scientific interest in the study of the biomechanical and hydrodynamic properties of sportswear for swimming has increased significantly. Studies show that swimming efficiency depends not only on the athlete's level of technical preparedness, but also on the characteristics of the body surface, clothing materials, and their interaction with the aquatic environment [1,3].

Toussaint and Truijens [1], analyzing the external forces and resistance mechanisms arising during swimming, note the important role of the hydrodynamic properties of the surface of sportswear. In addition, studies devoted to Fastskin-type swimsuits have shown that the material and surface structure of clothing are capable of reducing hydrodynamic resistance [3,4]. In swimming technique, rotational movements of the body and its kinematic characteristics are also of significant importance. Studies conducted by Sanders and Psycharakis [2] indicate that rotational body movements impose increased requirements on the deformation properties of clothing in the lateral zones, which determines the necessity of applying a zonal approach to elasticity in sportswear design.

From the perspective of materials science, the mechanical properties of knitted and elastic materials used in sportswear for swimming have been studied in sufficient depth [6,7]. It has been established that material thickness, elastic modulus, and recovery properties largely determine the biomechanical efficiency of clothing. In addition, a positive effect of compression garments on muscle activity and movement stability of the athlete has been identified [8,9]. These results expand the possibilities for the application of compression panels adapted to functional muscle zones in the construction of sportswear for swimming. In modern studies, methods for analyzing three-dimensional movements and garment deformations are also widely applied [11], making it possible to identify complex biomechanical interrelationships between body movements, muscular load, and deformation of clothing materials.

In modern sports biomechanics, sportswear is regarded as an active system that exerts an indirect influence on the effectiveness of an athlete's motor activity. This is particularly relevant for complex coordination and high-speed water sports, such as kayak slalom, where the biomechanical adaptability of clothing design acquires special importance.

In this sport, the athlete performs paddling movements with a double-bladed paddle while being in a seated position and alternately working on both sides. As a result, a continuous process of force transmission between the upper and lower body segments is formed. The present article is not aimed at developing a new model of sportswear, but is focused on determining the theoretical and functional requirements for sportswear design based on a biomechanical analysis of paddling movements in kayak slalom.

From a biomechanical point of view, the elasticity of sportswear contributes to a reduction in mechanical resistance in the joint areas. During paddling, the shoulder, elbow, and wrist joints undergo the greatest angular changes. Insufficient elasticity of clothing materials may lead to compensatory muscle overstrain and disruption of paddling technique [3,5]. In this regard, the use of zonal panels made of highly elastic fibers in clothing for kayak slalom athletes is biomechanically justified.

Biomechanical Description of the Stroke in Slalom Kayaking

The stroke in slalom kayaking has a cyclical, alternating, and rotational nature. During the movement, a kinetic chain is formed in the body, meaning that force is sequentially transmitted from the lower body segments to the upper ones and then to the paddle. The sequence of force transmission is as follows: foot → thigh → pelvis → spine → shoulder → elbow → forearm → paddle. In this process, the athlete’s body is in a state of dynamic stability, maintaining balance under conditions of water flow and slalom obstacles. The spine constantly experiences torsional movements, which leads to a high load on the muscles of the lower back and abdomen (Figure 1). The stroke in slalom kayaking is divided into the following main phases: paddle immersion in water, force generation, paddle extraction from water, and change of stroke side. During this, the athlete’s body maintains dynamic stability, preserving balance under conditions of water flow and turns.

Entry **Vertical** **Exit**

Figure 1. Correspondence of movement zones, muscles, and equipment in a professional slalom kayak athlete during the stroke

Paddle Immersion Phase: In this phase, the paddle is precisely and quickly immersed in the water, creating the conditions for subsequent force generation. During this period, shoulder joint flexion, spinal rotation, and active pelvic movement are observed. The primary actively engaged muscles include the deltoids, latissimus dorsi, and oblique abdominal muscles.

Force Generation Phase: The force generation phase represents the stage of maximal biomechanical load. During this period, concentric muscle contraction predominates. The main muscles involved are the latissimus dorsi, spinal extensors, and thigh muscles.

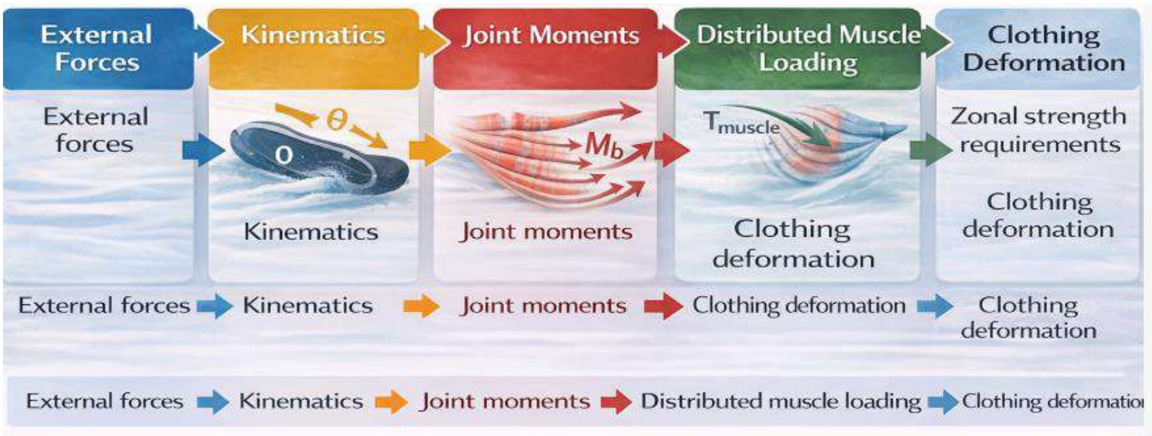
Paddle Extraction Phase: During paddle extraction from the water, precise coordination of the elbow and wrist joints is particularly important. The muscles predominantly work in an eccentric contraction mode.

Stroke Side Change Phase: The stroke side change phase is characterized by a rapid transition from the left to the right side. During this period, continuous activity of the abdominal muscles and shoulder stabilizers is observed.

Biomechanical Requirements for Sportswear Design (Theoretical Analysis):

Sportswear for slalom kayak athletes must simultaneously provide freedom of movement, rotational adaptation, muscle stabilization, and heat exchange. High elasticity in the shoulder and arm areas, controlled compression in the lower back and spine, as well as the presence of ventilation panels on the back, have a biomechanical justification.

During the stroke, kinematic parameters arising under the influence of external forces generate moments in the joints, which lead to distributed loading on the muscles. As a result of these loads, the clothing material undergoes deformation, based on which the requirements for strength and elasticity for individual body zones can be determined. The biomechanical features of the stroke in slalom kayaking dictate the application of a zonal approach in sportswear design. In Figure 2, the functional zones of body activity in various stroke phases are highlighted with colors and analyzed taking into account the biomechanical requirements for clothing. Water resistance and inertia forces determine the speed of movement and the trajectory of the athlete's stroke.



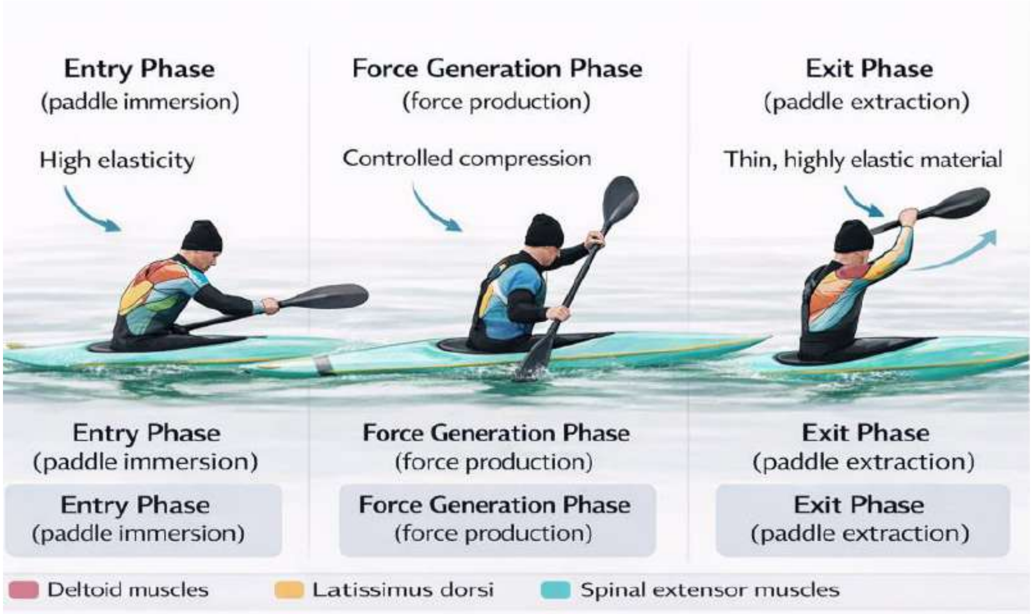


Figure 2. Functional zones of body activity during different phases of the stroke

These forces directly affect the amplitude and acceleration of movement at each phase of the stroke cycle. As a result, the movement velocities and angular changes generate torques in the shoulder and hip joints. These torques are balanced by the muscles. The magnitude of the joint torque determines the force and level of muscle activity. High torques create uneven and intense loads on the muscles. Due to muscle contraction and changes in muscle volume, the clothing material experiences stretching, local pressure, and shear deformations. In areas with intense deformation, materials with high elasticity and strength are required, while in relatively stable zones, moderate compression is sufficient.

The zone marked in blue — the high-elasticity area covering the shoulder girdle and upper arm region. This zone allows unrestricted flexion, extension, and rotational movements of the shoulder joint during the stroke. In the garment design, this section is made of elastic material that does not limit the range of motion.

The zone marked in red — a diagonal elastic panel located along the sides of the torso and abdominal muscles. This zone adapts to the rotational movements of the torso, ensuring continuous force transfer. The design solution reduces rotational load during the stroke.

The zone marked in green — the controlled compression area covering the lower back and spine. This section provides functional stability to the muscles and supports body posture during the power phase while simultaneously preventing excessive muscle fatigue.

The zone marked in yellow — a mesh elastic panel on the central part of the back and lower back. This zone offers high breathability and improves heat exchange during intense physical activity, while also providing light muscle stabilization.

The zone marked in gray — the minimal-resistance movement area, covering the wrists and elbows. The garment design in this section is simplified to the maximum, reducing water resistance and allowing free movements at high speed.

In a slalom kayak, the spine is constantly subjected to torsional movement, creating high loads on the lower back and abdominal muscles. This is taken into account in the garment design through anatomical panels on the back and elastic zones in the lower back area, enabling natural spinal movements.

Lower Body Biomechanics

In a slalom kayak, the lower body is not passive but performs the following functions:

- Stabilizing the boat;
- Supporting rotational movements;
- Initiating force transfer.

Accordingly, the garment must provide:

- Sufficient elasticity in the hip and pelvis area
- A pre-shaped cut that accommodates knee flexion.

Biomechanical Effects of Compression Sportswear

Scientific studies show that lightweight compression garments:

- Reduce muscle oscillation;
- Enhance proprioception (the body’s sense of position);
- Delay the onset of muscle fatigue.

For slalom kayaking, the use of zonal compression is rational. This sport is characterized by high speed, sharp turns, and continuous rotational movements. Only by designing sportswear based on biomechanical principles can the efficiency of an athlete’s movements be improved. An ergonomic design, elasticity matched to muscle activity, and the use of modern materials allow athletes to fully realize their functional potential.

Comparative Analysis of Slalom Kayakers’ Sportswear from a Biomechanical Perspective: Sportswear has a varying impact on movement efficiency in slalom kayaking. Therefore, this study compared three types of sportswear used by professional athletes based on a unified biomechanical movement model. The main evaluation criteria were range of motion, muscle activity, movement resistance, and the athlete’s functional comfort.

Lightweight Slalom Sportswear (Based on Elastic and Hydrophobic Materials)

Lightweight slalom sportswear is primarily made from materials with high elasticity, low water absorption, and quick-drying properties. This type of clothing provides maximum freedom of movement for professional slalom kayakers. Biomechanical analysis shows that rotational movements in the shoulder joint, spine, and pelvic area are virtually unrestricted. This is especially evident during the paddle extraction and side-switching phases, when movement speed remains high.

However, the level of muscle support is relatively low, so during prolonged exertion, muscle fatigue occurs more quickly. Lightweight sportswear allows for maximum range of motion, but its capabilities in terms of muscle stabilization and thermal protection are limited.

Neoprene-Based Wetsuit: Neoprene wetsuits are widely used in water sports, providing a high level of thermal protection and passive muscle stabilization. In slalom kayaking, a neoprene suit helps maintain the athlete's body temperature and reduces muscle vibrations. At the same time, biomechanical analysis shows that the relative stiffness of neoprene somewhat restricts torsional movements of the shoulder joint and spine. This limitation is especially noticeable at high speeds during slalom turns and rapid transitions between phases. A neoprene wetsuit increases muscle stabilization and thermal protection but imposes biomechanical constraints on high-speed rotational movements.

Hybrid Sportswear (Based on Neoprene and Elastic Zones)

Hybrid sportswear is designed to combine the protective properties of neoprene with elastic panels. This type of clothing is considered the most balanced biomechanical solution for professional slalom kayakers. Analyses show that the use of highly elastic panels in areas responsible for shoulder, lower back, and spinal rotation preserves the range of motion. At the same time, neoprene segments placed over the muscles provide passive stabilization and reduce fatigue. As a result, the athlete is able to maintain high speed and precision over extended periods.

Hybrid sportswear offers an optimal balance between freedom of movement and muscle stability, making it the most suitable option for professional slalom kayakers.

Hybrid Sportswear (Based on Neoprene and Elastic Zones) Hybrid sportswear is designed to combine the protective properties of neoprene with elastic panels. This type of clothing is considered the most balanced biomechanical solution for professional slalom kayakers. Analyses show that the use of highly elastic panels in areas responsible for shoulder, lower back, and spinal rotation preserves the range of motion. At the same time, neoprene segments placed over the muscles provide passive stabilization and reduce fatigue. As a result, the athlete is able to maintain high speed and precision over extended periods. Hybrid sportswear offers an optimal balance between freedom of movement and muscle stability, making it the most suitable option for professional slalom kayakers.

Biomechanical Analysis of the Correspondence Between Movement Zones, Muscles, and Clothing in Slalom Kayakers

The assessment was conducted based on the following methodological principles:

- The cyclical and rotational nature of movement;
- Modes of concentric and eccentric muscle contraction;
- Mechanical properties of the clothing material (elasticity, compression, friction).

Table 1. Correspondence Between Movement Zones, Muscles, and Clothing

Phase of Movement	Active Muscles	Body Area	Clothing Feature
Catch (Immersion)	Deltoids, latissimus dorsi, oblique abdominal muscles	Shoulders–chest	High elasticity
Power (Force Generation)	Latissimus dorsi, spinal erectors	Back–lower back	Zonal compression
Exit	Triceps, forearm muscles	Elbow–wrist	Minimal resistance
Transition (Side Switch)	Oblique abdominal muscles, stabilizers	Torso area	Symmetrical elasticity

The conducted biomechanical analysis shows that in slalom kayaking, maximum efficiency is achieved only when the design of functional zones in sportswear aligns with the phases of movement. It is particularly important that zonal elasticity and controlled compression during the force-generation and side-switch phases enhance the athlete's technical stability.

Based on this model, the developed hybrid sportswear was evaluated as the biomechanically optimal option for professional slalom kayakers. Clothing designed with consideration of the correspondence between movement zones, muscle activity, and structural elements contributes to improving the efficiency of the athlete's movements. Zonal elasticity, a design adapted to rotational movements, and solutions that support muscle activity create conditions for enhanced athletic performance.

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