Chapter

Peculiarities of Muscle-Tendon Mechanics and Energetics in Elite Athletes in Various Sports

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Abstract

The article presents results of the research on jumping strategies applied by elite athletes in various sport disciplines. Research hypothesis: to perform the same motor task athletes employ different ways of organizing the movement and different features of MTU functioning. The choice of a mechanism to enhance muscle contraction depends on sport discipline, in particular specific features of the sport movement. The study involved members of the Russian national teams in alpine skiing, bobsleighing, mogul skiing and ski jumping. The athletes performed drop jumps from the heights of 0.1, 0.3, and 0.5 m with no arm swing. Experimental data were obtained online from 24 cameras using the Qualisys motion capture system (400 frames per second) and the two force plates AMTI 6000. Data was processed using the OpenSim package. The authors calculated the amount of accumulation and utilization of elastic strain energy and assessed metabolic energy expenditures in MTU. The authors concluded that employment of different strategies of movement organization in drop jumps could be explained by the transfer of motor skills specific to the athlete's sport discipline. The results of the study may help coaches develop individual training plans for athletes, in particular strength training exercises targeting specific muscle groups.

Keywords: muscle-tendon unit, drop-jump, OpenSim, elite athlete, elastic energy

1. Introduction

Elastic strain energy is stored in tendons and is used in various motor tasks. It permits to minimize energy costs of muscle contraction and increase power output of muscle-tendon units (MTU). Therefore, specific mechanical properties of different tendons can influence MTU behavior and, ultimately, mechanical power and muscle efficiency of movements [1].

It was suggested that there was a relationship between the structure of various mammalian tendons and their role in effective transmission of force or energy conservation during elastic deformation [2]. The relevance of this idea lies in the context of improving results in various sport movements due to conformity of MTU functioning with requirements and specific features of a sport discipline.

This article presents research data on various strategies used for power production by MTU of the lower extremities in drop jumps. According to the hypothesis [3], to perform a motor task, a muscle develops power that should be adequate to mechanical requirements of the task in order to produce a movement. Any movement is determined by timing, sequence and amplitude of muscle activation. Two elastic mechanisms contribute to the efficiency of power production in multi-joint movements of the lower extremities during a take-off: pre-stretch of skeletal muscles and mechanical energy transfer via biarticular muscles. It is assumed that the extent to which each of the mechanisms is used exerts effect on the strategy of organization of multi-joint movements.

Preliminary stretching of skeletal muscles is the first mechanism to increase power of a take-off. It is known that pre-stretch of the muscle-tendon complex (MTU) amplifies strength of its subsequent contraction [4, 5]. This mechanism manifests itself in various movements, including vertical jumps [6–8].

The second mechanism of increasing power of a take-off (mechanical energy transfer) was described in a few works related to running, hopping and vertical jumping [3–5, 9–12]. The mechanism of mechanical energy transfer via barticular muscles is also associated with the effects occurring in the MTU [13, 14].

Enhancement of MTU contraction can be reached with the help of three mechanisms: accumulation and release of elastic deformation energy, activation of spinal reflexes, and muscle potentiation. Many studies related to this topic were carried out in both animals and humans. They showed that several mechanisms could be activated simultaneously in the stretch-contraction cycle in order to enhance the MTU contraction. Those mechanisms could vary depending on external conditions and motor tasks [15–23]. For example, in running and hopping it is necessary to maintain muscle strength that is achieved by the use of MTU elastic strain energy; in accelerations, starts and jumps the catapult mechanism is used; and in landing energy is absorbed due to muscle compliance [24]. Such variability in performance of different motor tasks is achieved by modulating the muscles' intrinsic mechanical properties due to spinal reflexes, which can increase or decrease muscle stiffness [25–27]. So, it is possible to use the elastic deformation mechanism in muscles or, conversely, the muscles can act as a damper in landing. It is assumed that the choice of this or that mechanism depends on the character and requirements of the sport exercise, and athletes from different sports may demonstrate difference in organization of MTU control.

We hypothesized that to perform the same motor task athletes could employ different ways of movement organization. An athlete's preference when choosing this or that mechanism for enhancing power of muscle contraction depended on specific features of sport discipline, notably, requirements to the main sport exercise.

From a practical perspective, our research was aimed at obtaining data that could be used in training of top athletes. Strength training is an integral part of athletic training in sport of top results, and it is effective only when it is based on individual characteristics of elite athletes. The results of this study will help coaches develop individual training plans for athletes, in particular strength training exercises targeting specific muscle groups.

2. Methods

The study involved male members of the Russian national teams in alpine skiing n = 4, bobsleigh n = 5, mogul skiing n = 5 and ski jumping n = 5 (**Table 1**). All athletes took part in the World Cups and World Championships. The experiment was carried out within the framework of regular testing of national team members according to established protocols in the course of preparation for international competitions [28].

	Alpine skiing	Mogul skiing	Bobsleighing	Ski jumping
Weight (kg)	82,4 ± 4,3	73,5 ± 2,3	108,9 ± 6,5	69,1 ± 1,7
Height (m)	1,79 ± 3,1	1,66 ± 2,4	1,89 ± 2,5	1,78 ± 2,1
Body mass index (m/kg°)	25,7 ± 6,5	26,6 ± 5,4	30,4 ± 7,8	20,3 ± 2,8
% of muscles in the body (%)	53,4 ± 7,5	34,1 ± 6,7	49,1 ± 8,1	51,6 ± 2,4
Experience (y)	10,1 ± 3,1	7,8 ± 1,8	11,4 ± 2,8	8,9 ± 2,2

Table 1.
Characteristics of the subjects. Mean ± SD.

Testing procedure. After a warm-up subjects performed drop jumps (vertical jumps after jumping down) from the height of 10 cm, 30 cm, and 50 cm with no arms swing. The subjects were advised to wear their preferred athletic shoes and to keep hands on the hips during the jumps. The best of three trials, regarding jumping height (CoM elevation), was considered for further analysis. Rest interval between the trials was about 2–3 min depending on the individual need of the athlete.

Data Processing Approach. The software complex received input data of real movement from by the Qualisys Motion Capture System (24 cameras Oqus 5 Qualisys, Sweden). Jumping exercises were performed on two force plates AMTI 6000 (AMTI, USA). Recording was done at frame rate 400 fps and synchronized with force plate's signals. The data were processed with the help of the software package OpenSim [29]. The software package permitted to create an individual musculoskeletal model of every athlete and identify specific features of his movement technique.

Kinematic and dynamic calculations were performed using simulation of a full-body model proposed by the Hamner and Delp paper [30]. We used a three-dimensional musculoskeletal model with 29 degrees of freedom, 92 muscles of the torso and lower extremities driven by torque actuators. This model was previously used to study how each muscle contributes to accelerating the body's center of mass during a jump [30, 31]. The model included 35 lower limb muscles, 5 of which were examined in this study. To analyze metabolic costs during the jump experiment, we selected a group of key muscles involved in the take-off phase of a vertical jump: Gl (gluteus maximus, gluteus medius, gluteus minimus muscles), RF (rectus femoris), VAS (vast medial muscle), GAS (lateral sections of the gastrocnemius muscle), SOL (soleus muscle).

An individual muscle and tendon complex was described by a three-piece MTU model, based on Thelen's work in 2003 [32], modified by few other authors [33, 34] and implemented in the OpenSim application. The model calculated the change in length and strength of muscles and tendons over a wide range of body positions. The model also permitted to study in detail functioning of the MTUs of the ankle, knee and hip joints when generating force and its derivatives for each subject. We simulated each jump with the help of the methods described by Hamner and Delp [30].

Our simulation workflow began with scaling the geometry of the generic musculoskeletal model to match the anthropometry of each of our subjects, using the OpenSim Scale Tool. In addition, we scaled the maximum isometric forces of the muscles according to a regression equation based on each subject's mass and height [31]. Then we generated muscle driven motions of the recorded experiments with OpenSim's Computed Muscle Control (CMC) Tool [32], using the individual models and the adjusted kinematics. CMC calculated muscle excitations that could produce the observed jumping motion while minimizing the sum of squared muscle activations at regular intervals in the motion.

Elastic Strain Energy (ESE) Calculation. During the analysis we attempted to calculate the possible amount of stored and utilized elastic strain energy (ESE) using methods suggested by [4, 35]. According to the authors mechanical energy expenditures (MEEs) of two human lower extremity models are associated with two different sources of mechanical energy - (1) muscles and (2) joint moments. The source of mechanical energy in the Model 1 was a group of eight muscles, three of them being two-joint muscles. The source of mechanical energy in the Model 2 was a set of net moments in its joints.

It was shown that the model with two-joint muscles spent less mechanical energy than the model with no two-joint muscles in the same movement. Saving of mechanical energy by two-joint muscles was possible on condition that: (i) muscle powers produced by the two-joint muscle at both joints were of opposite signs, (ii) moments produced by that muscle at each of the two joints were codirectional with the net joint moments at those joints, and (iii) biarticular antagonist muscles did not produce force.

Metabolic Costs Calculation. To estimate metabolic energy consumption, we used a metabolics model developed by [36, 37] with few modifications by [36]. To employ this metabolic model, we used the Umberger2010MuscleMetabolicsProbe in OpenSim v4.

In accordance with the calculation method, we summed the rate of energy expendutures of all muscles, added a basal rate (1.2 W/kg – [38]).

Leg Stiffness Calculation. We estimated leg stiffness:

$$K_{leg} = F_{max} / \left(\left(l_o - l_{min} \right) / l_o \right), \quad (1)$$

where K_{leg} – the leg stiffness normalized to body weight as the ratio of the peak vertical ground reaction force (F_{max}) to the difference between the leg length when standing and the leg length when the center of mass is at its lowest point lmin. The leg length l0 was the distance from the center-of-pressure [39] to the center of the pelvis in a model derived from the musculoskeletal model described by [40].

To process the results of our research we used a software package STATISTICA ver.10. As we had small sample sizes, we used non parametrical statistical methods: Kruskal-Wallis test and Wilcoxon test.

Ethical Approval. The study was approved by the Local Human Research Ethics Committee, and all participants gave their written informed consent prior to testing. All human testing procedures conformed with the principles of the Declaration of Helsinki.

3. Results

Figure 1 demonstrates multidirectional changes in the maximum peak power in drop jumps from different heights performed by the subjects. Mogul skiers showed negative dynamics of the maximum peak power as the height of the drop jump increased: the maximum peak power in drop jumps from the height of 0.1 m and 0.3 m differed by 2.67 ± 0.05 W/kg ((T = 0,0, p = 0,043), the difference of the maximum peak power in drop jumps from the height of 0.3 m and 0.5 m was 2.89 ± 0.07 W/kg (T = 0,0 p = 0,041). All the other subjects (alpine skiers, bobsledders, and ski jumpers) showed positive dynamics of maximum peak power. The greatest maximum peak power was reached in the group of ski

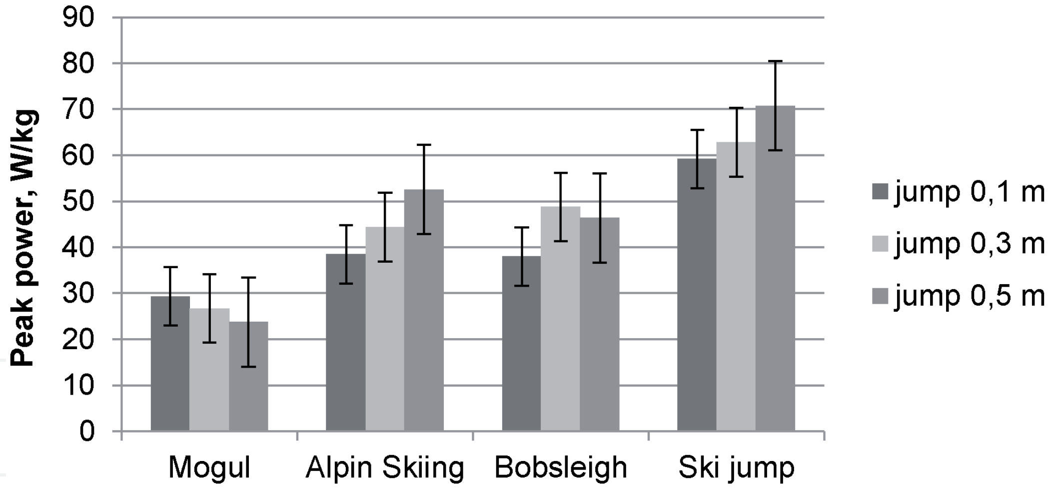

Figure 1.
The maximum peak power in the take-off phase.

jumpers (0.1 m – 59.2 ± 0.23 W/kg; 0.3 m – 62.8 ± 0.30; 0.5 m – 79.8 ± 0.56 W/kg), while the lowest – in the group of mogul skiers (0.1 m – 59.2 ± 0.27 W/kg; 0.3 м – 62.8 ± 0.23 W/kg; 0.5 м – 79.8 ± 0.46 W/kg) . Mogul skiers demonstrated significant difference in maximum peak power in comparison with the other athletes (H = 8,22003 p < 0,01).

Time of the take-off phase (**Figure 2**) significantly differs in ski jumpers (0,1 м - 0,18 ± 0,06 s; 0,3 м - 0,215 ± 0,05 s; T = 8,32117, p > 0,01; 0,5 м - 0,23 ± 0,07 s; T = 8,32117, p > 0,01) and in athletes from the other groups. The average time of the take-off in the groups of bobsledders, alpine skiers and mogul skiers was 0.11–0.13 ± 0.02 s in all jumps, while in ski jumpers it was 0.18–0.23 ± 0.05 s (H = 8,32117, p < 0,01).

If we compare **Figures 1** and **3**, we will note that the athletes achieved different power of movement on the background of different leg stiffness. The maximum leg stiffness was registered in alpine skiers in drop jumps from 0.1 m – 23659.6 ± 1182 N/m, bobsledders in drop jumps from 0.3 m – 24384,9 ± 987 N/m, and mogul skiers in drop jumps from 0.5 m - 23608,8 ± 1243 N/m; the minimal leg stiffness was registered in ski jumpers (0.1 m - 14463,4 ± 723 N/m; 0.3 m - 9206,8 ± 803 N/m and 0.5 m - 7115,1 ± 654 N/m). The difference between the groups was significant (H = 8.75356, p < 0.01), the dynamics of data within each group was different. Mogul skiers demonstrated the maximum values in leg stiffness in drop jumps from 0.5 m. In alpine skiers

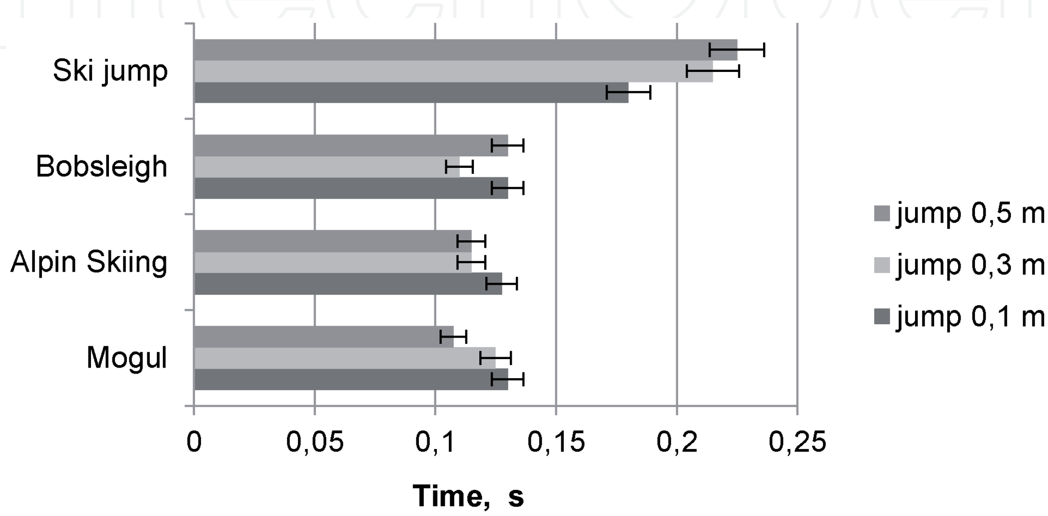

Figure 2.
Time of the take-off phase.

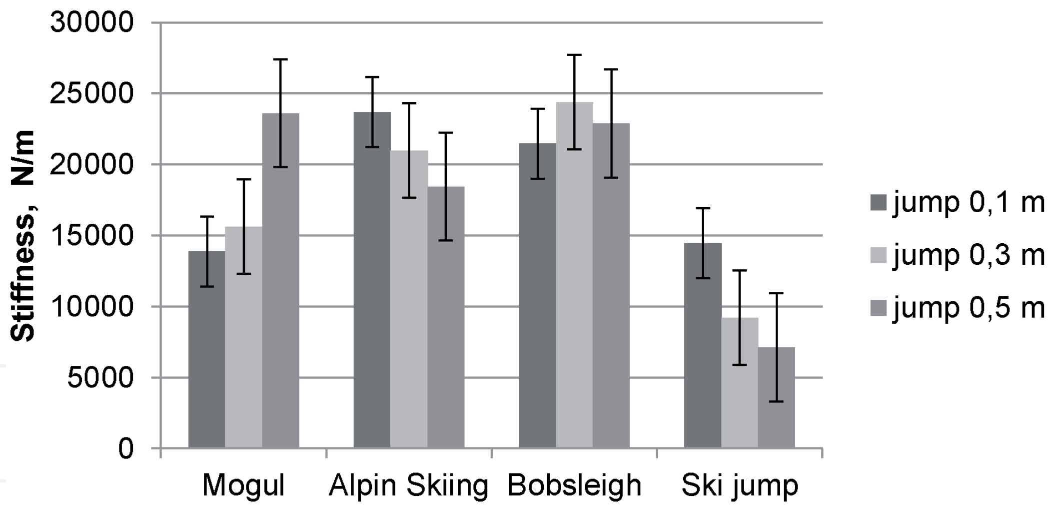

Figure 3.
Peak value of the stiffness of the muscles of the lower extremities in drop jumps.

and ski jumpers the maximal leg stiffness was found in drop jumps from 0.1 m. The small height may permit these athletes to perform preliminary muscle stimulation before landing that makes it possible to counteract external inertial forces acting on the body. When the height is greater, athletes try to compensate loads on the musculoskeletal system in shock absorption phase by increasing the amplitude of movement in the knee joints, thereby reducing the stiffness of the legs. In bobsledders leg stiffness in the jump from 0.5 m was 6.5% lower than that in the jump from 0.3 m. It might be that the bobsledders tried to keep high leg stiffness, but as they were heavy, their muscles could not resist the load in the eccentric phase.

Energy transfer between the muscle groups of the lower extremities during the concentric contraction phase of the take-off was calculated using the method described in [4, 35] (**Figure 4**). We found that the mechanism of energy transfer was almost not used by ski jumpers (Hip-Knee: 3–6%, Knee-Ankle: less than 3%, H = 8,564 p < 0,01). The highest percentage of energy transfer was found in bobsledders (Knee-Ankle: 28 ± 0.8% in a drop jump from 0.3 m, 25 ± 0.7% in a drop jump from 0.5 м) and alpine skiers (Hip-Knee: 23 ± 0.4% from 0.3 м), but the segments

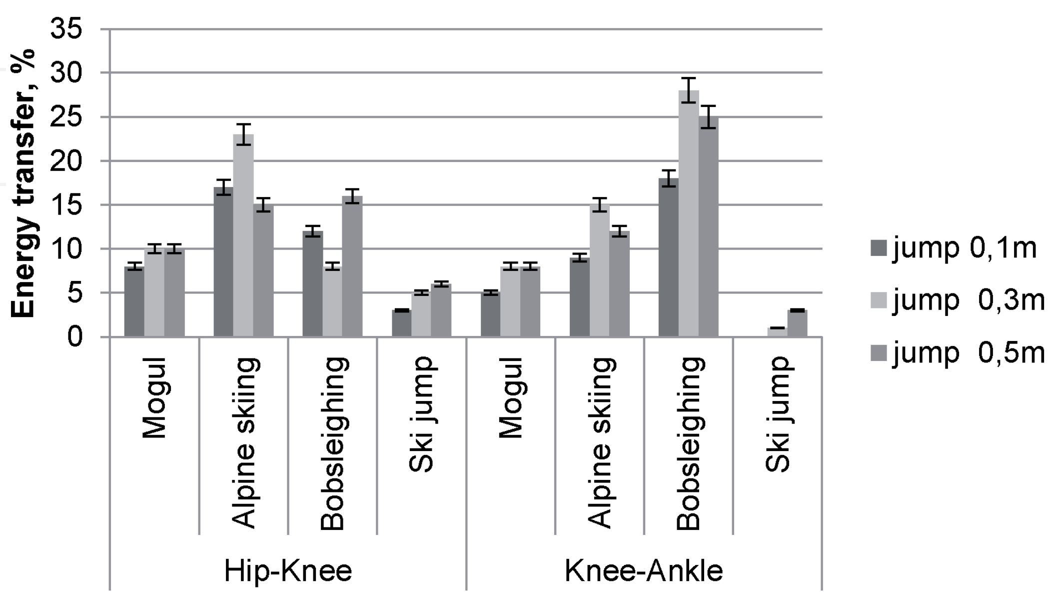

Figure 4.
Transfer of energy between muscle groups of the lower limbs in the take-off phase (concentric muscle contraction).

of the lower limbs mostly involved in the energy transfer were different in those two groups. In bobsledders the highest energy transfer occurred from the thigh muscles to the lower leg muscles via the knee joint, while in alpine skiers energy transfer between the hip extensors and the thigh muscles was the highest. Mogul skiers showed a very low energy transfer from the hip extensors to the thigh muscles and almost no energy transfer from the thigh muscles to the lower leg muscles via the knee joint.

Gl - gluteus maximus, gluteus medius, gluteus minimus muscles, RF - rectus femoris, VAS - vastus medialis, GAS - lateral sections of the gastrocnemius muscle, SOL - soleus muscle.

The highest peak metabolic costs of all lower extremities muscles were found in mogul skiers (**Figure 5**). In all athletes peak metabolic costs of the hip extensor (Gl) tended to decrease, as the height of drop jumps increased, because athletes tried to maintain more upright posture for stability. All athletes had the lowest peak metabolic costs in GAS. In mogul skiers the maximum metabolic costs in GAS were registered in drop jumps from the height of 0.1 m (40.9 ± 2.5 W); in ski jumpers the minimum metabolic costs in GAS were registered in drop jumps from the height of 0.5 m (7.2 ± 1.2 W). High peak metabolic costs in RF and VAS were found in all athletes (87.2–73.1 and 105.1–74.6 W, correspondingly). As the height of drop jumps increased, the metabolic costs in RF and VAS_L increased in mogul skiers and decreased in alpine skiers. The total metabolic costs increased in mogul skiers and ski jumpers, were stable in alpine skiers, and decreased in bobsledders, when the height of drop jumps increased.

Gl - gluteus maximus, gluteus medius, gluteus minimus muscles, RF - rectus femoris, VAS - vastus medialis, GAS - lateral sections of the gastrocnemius muscle, SOL - soleus muscle.

The peak force in the tendon of the MTU model involved in the take-off is shown in **Figure 6**. Ski jumpers had the lowest peak force in the tendon in comparison with the other subjects for all muscles and in all drop jumps. Alpine skiers, bobsledders and mogul skiers demonstrated active work in the tendons of the GAS and SOL muscles, as well as positive dynamics, as the height of drop jumps increased. Tendon activity of VAS in mogul skiers and alpine skiers revealed similarity in magnitude and positive dynamics. The greatest peak activity of the Gl tendons during the take-off was observed in alpine skiers when drop jumping from a height of 0.5 m (108.3 ± 6.7 N).

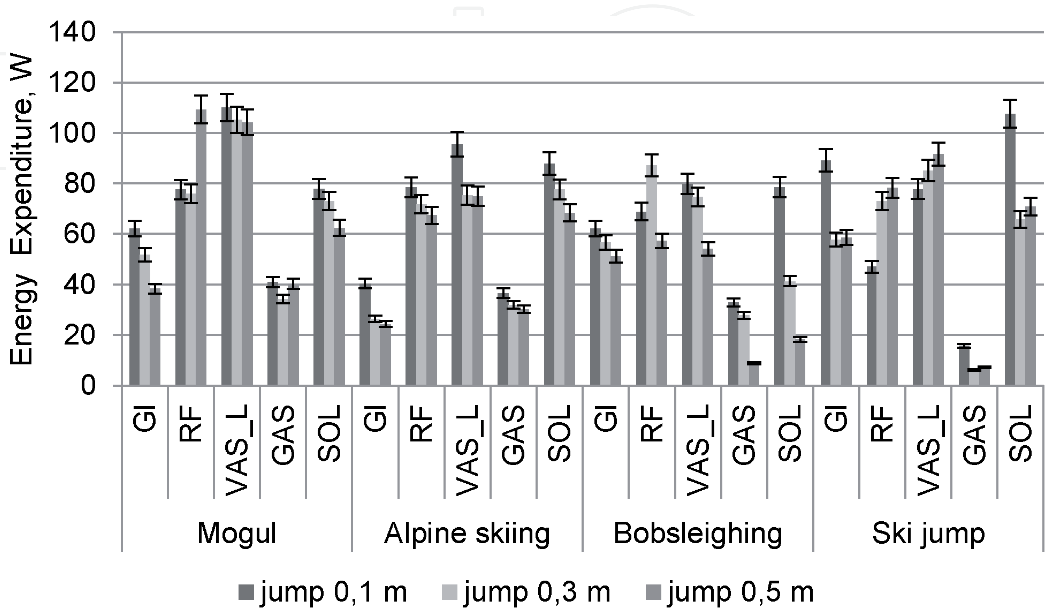

Figure 5.
Metabolic expenditures in simulated muscles.

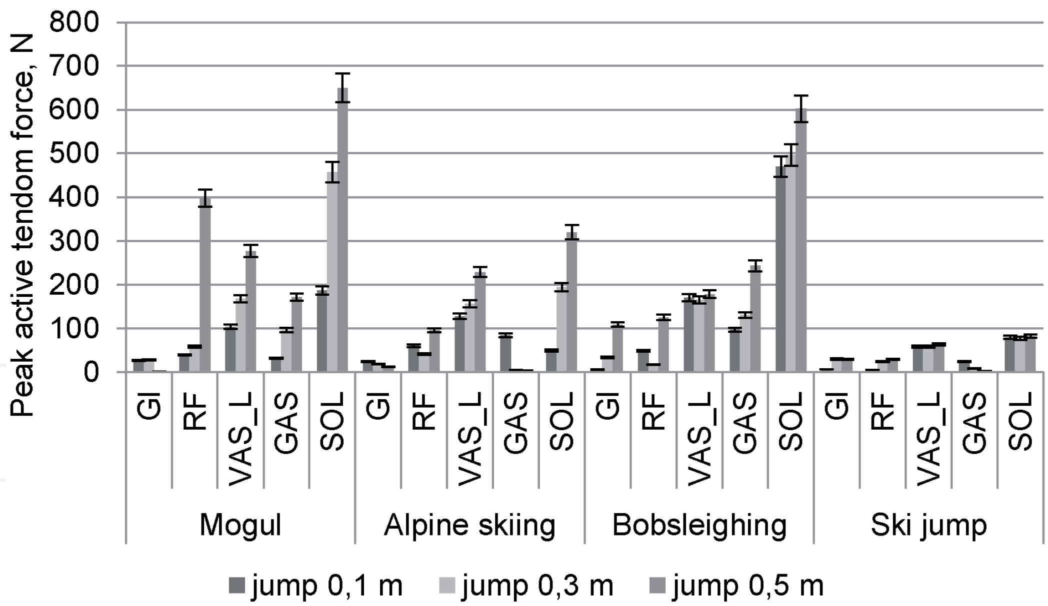

Figure 6.
Peak active tendon force.

4. Discussion

To understand the peculiarities of the MTU work in athletes of four different sport specializations, it is necessary to briefly present specific features of those sport disciplines.

4.1 Alpine skiing

Alpine skiing includes four disciplines, which are divided into technical disciplines (slalom SL, giant slalom GS) and speed disciplines (super giant SG, downhill DH). In slalom (SL) the peak ground reaction force (GRF) being a measure of the external load on the skier and equipment, can reach five times the body weight of an athlete [41]. In three other alpine skiing disciplines the highest GRF values are observed in giant slalom [42]. The main muscles involved in alpine skiing are the thigh muscles, hamstrings, quads, calves, and foot muscles [43]. Most of the muscles involved in alpine skiing contract eccentrically during the race. This means that the muscle lengthens as it contracts. The contraction rate during downhill skiing is relatively slow compared to running or jumping. This is due to the fact that, for example, the angle of the hip does not change significantly during a ski turn, so the rate of contraction is relatively low. Alpine skiing requires fast movements with multiple maximum contractions. Compared to other athletes, alpine skiers have high isometric leg strength [44] and isokinetic leg strength, measured as maximum torque during knee extension [45]. In technical disciplines, a "quasi-static" component of skiing has already been proposed because of the evidence for coactivation during contraction of the thigh muscles [46]. Evidence from elite Swiss riders confirms that eccentric muscular work prevailed over concentric work in the SL, GS and SG disciplines [47]. Authors [47] claimed that alpine skiing is "the only sport in which eccentric muscular activity predominates" [47]. Higher levels of force allow the skier to work with less relative strength, which can lead to more control in turns (less energy dissipation) and less fatigue when racing.

4.2 Mogul skiing

Mogul skiers have to overcome irregularities in the form of bumps and pits when descending from the mountain. On a mogul course, the turns to the left and right of the downhill line are always made cyclically, without any separate transition phase between individual turns. An athlete goes around the hillocks on the descent. He/she makes a turn at each bump that forms the so-called "swinging rhythm". Mogul skiing is characterized by clearly identifiable ski loading and unloading phases, and alteration of ski bending and unbending. The load, being almost evenly distributed between both skis, reaches the maximum value of about 150% of the skier's body weight on each ski. The technique obliges athletes to move along the track with an angle at the knee joints close to 90° to ensure the minimum deviation of the CoM trajectory. This stance allows a skier to cushion the height differences of bumps and pits, while maintaining and controlling the speed. According to the data of [48, 49], it was shown that in mogul skiers, in contrast to alpine skiers, the ratio of eccentric/concentric patterns is close to those in running.

4.3 Bobsleighing

A standard bobsled race may be divided into three phases: start, race and finish [50]. Acceleration and high speed at the end of the start phase are crucial for high bob speed during a race and a better overall result [50, 51]. At the start phase, athletes must start the race by pushing the bob within 60 seconds after the start signal and run at full speed about 55 m. The start and push phases last for only 6 seconds, but they are the most important for the final result [52]. To perform a push-start, leg extensors must generate high mechanical power in the hip, knee and ankle joints to create significant horizontal propulsive force that propels the athlete's body and bob forward. Previous studies reporting the electromyographic (EMG) activity in sprinters in the acceleration phase have shown that biceps femoris (RF) is one of the most important muscles for developing maximum speed [53]. Similar as at the start of a sprint run, the longer running distance increased workload of the plantar ankle flexors [52].

4.4 Ski jumping

Take-off in ski jumping is a very important phase [54, 55], since it affects the initial flight phase. Three parameters indicating a change in body position during a take-off are important for the overall performance: (1) generation of angular momentum during a take-off [54, 56, 57]; (2) high speed of leg extension [54, 56, 57]; and (3) direction of a take-off [58–60]. Athletes perform a take-off in a quasi-static crouch position [57]. This position is necessary to maintain an effective aerodynamic posture and to resist the pressing external force acting on the body at a speed of about 90 km/h. According to [61], time from the start of the lower extremities extension and the rise of the athlete's center of gravity (COG) is about 0.22 ± 0.03 sec. The data presented in [62] indicate the time range of 0.25–0.30 sec. The study [59] examined the activity of the vastus lateralis muscle, vastus medialis, gastrocnemius, tibialis anterior and gluteus maximus. During acceleration on the jumping ramp the activity of all those muscles is very low. When an athlete enters the inner curve of the jumping ramp, the activity of the vastus lateralis, tibialis anterior and the gastrocnemius muscles grows that stabilizes the knee and ankle joints. Stable knees resist additional stress caused by the centrifugal force. The gluteus maximus remains inactive. During the take-off activity of the vastus lateral and the gastrocnemius muscles significantly increase. The tibialis anterior and gastrocnemius muscles are active to stabilize the ankle, but their activity is not greater than that registered at the curve of the jumping ramp. Greater activity of Gl at the end of the take-off results in an increase of moments in hip joints. Involvement of GA in the final phase of the take-off is considerably lower than in vertical jumps, in which plantar flexion plays very important role. A ski jumper rises skis quickly that does not allow him/her to use the gastrocnemius effectively, and knee extensors are the main muscles involved in the take-off. On the other hand, the design of ski jumping boots limit efficient plantar flexion during the take-off [62].

The data presented in the results section show that all groups of athletes chose different strategies for producing muscle power in order to achieve the maximum jump height in drop jumps. We will try to explain the mechanisms of work of lower extremities' muscles in athletes, who demonstrate different organization of movement and interaction of muscles and tendons in drop jumps. Let us examine ways of enhancing MTU contraction, which employ elastic properties of muscles, in particular, their resilient elements, that results in muscle potentiation. Besides that, enhancement of muscle contraction occurs due to stretch reflex, which manifests itself when the muscle is stretched for 20–50 ms [63] and even up to 60 ms [64]. There is no disagreement in the literature that the preliminary stretching of the MTU enhances its subsequent contraction, and this fact is described by many authors. However, with regard to the mechanisms underlying this phenomenon, many authors express doubts about the unambiguity of conclusions in favor of each of them, in particular, regarding the use of the energy of elastic deformation [65]. At the same time the use of the energy of elastic deformation in running and hopping is beyond any doubt. All doubts arise from the difficulty to examine human MTU behavior in vivo, in particular in complex multi-joint movements. Without inquiring into the mechanisms of MTU pre-stretching, let us discuss if the athletes participating in our study use the positive effect of MTU pre-stretch.

In the groups of alpine skiers and mogul skiers, duration of the take-off went far beyond the time limits where it was possible to use the positive effect of the stretch reflex. However, the subjects of these two groups could enhance voluntary contraction of their leg muscles due to elastic strain energy, even though the shock absorption phase was very long. Although an increase in the MTU stretching time reduced efficiency of elastic strain energy use, this mechanism was preserved [66]. We might be confused by the fact that the optimal ratio of muscle length and speed of their stretching is disturbed in alpine and mogul skiers because of large angular amplitudes of movements in leg joints. However, the use of elastic energy is still possible for any muscle length [67]. The question arises with regard to the use of the positive effect of shock absorption in drop jumps performed by alpine and mogul skiers. Question: Did the MTU work differ in these groups of athletes, since the technique of sport exercise was different? The answer is obvious - yes, it differed. This is confirmed by the data related to the transfer of elastic deformation energy between the lower extremities links. First of all, let us examine results of the drop jump from the height of 0.3 m, in which the load on the leg muscles is optimal for achieving the maximum jump height [68]. In the drop jump from 0.3 m the possible use of elastic energy in the take-off phase was: 23 ± 1.6% (Hip-Knee) and 15 ± 1.1% (Knee-Ankle) in alpine skiers, and 12 ± 0.6% (for Hip-Knee) and 8 ± 0.5% (for Knee-Ankle) in mogul skiers. Alpine skiers used energy transformation more effective than mogul skiers that was due to the higher stiffness of their leg muscles. The difference in the utilization of stored elastic energy between the subjects was visible when comparing metabolic costs in RF and VAS and tendon strength in these muscles, which were significantly higher in mogul skiers. In a drop jump from the height of 0.5 m the external load on the leg muscles was almost critically high. Mogul skiers showed a drop in mechanical power as well as an increase in RF metabolic costs and RF and VAS_L tendon strength. In both groups we found a decrease of elastic energy use. Referring to the difference in the requirements of a sport exercise, we may assume that there are no mandatory requirements for mogul skiers to generate maximum power during a mogul race, unlike for alpine skiers.

In alpine skiers, the decrease in efficiency of energy transfer might be associated with the decrease in stiffness in order to increase the role of muscle activity.

Bobsledders demonstrated the highest percentage of mechanical energy transfer. As the height of a drop jump increased, the metabolic costs of activation of the GA and SOL muscles decreased and the peak strength of tendons increased. These results indicate the use of the mechanism of transfer of mechanical energy generated during muscles pre-stretch. This mechanism can only be activated if the extension starts in the hip joint, which generates the greatest power. The energy transfer cannot occur instantaneously, because the bicarticular muscles need time to stretch and gain stiffness in order to reduce energy loss caused by dissipation [69]. When the hip joint extended due to Gl contraction, the energy was transferred to the shin via the RF, then it took time for the GA to be activated after the start of the knee extension. Elastic energy was stored in the tendons of the ankle extensors and then it was released quickly. The MTUs of the muscles acted as an adjustable spring, and the contractile component modulated the energy required for fast limbs extension. Thus, leg extension occurred with successive achievement of peak power values in each of the joints and peak values of the linear velocity of the leg links in the direction from the proximal joint to the distal one. In fact, energy transfer in squat jump and counter movement jump occurs exactly this way [3, 70–72]. As a result, the ankle joint being controlled by the weakest muscle group, can develop greater power due to the energy received from the proximal joint [3]. Thus, to achieve maximum muscle power, bobsledders used conjoint work of both muscles and tendons that permitted them to make use of the mechanism of energy transfer based on the pre-stretch effect. The group of bobsledders included former track-and-field athletes. To push the bob, they extended the lower extremities using similar range of articular angles as in drop jumps. According to our data, it can be assumed that ski jumpers have no technical skills to increase muscle power in a take-off using additional mechanisms besides muscle activity. The ski jumpers showed the longest take-off time in drop jumps, and it corresponded to the take-off time from the take-off table in their sport exercise. In accordance with the temporal characteristics of the take-off, we may assume that ski jumpers do not use the effect of stretch reflex. High metabolic costs of muscle work and small forces in the tendons indicated that the ski jumpers used only muscle strength to perform drop jumps from different height and did not employ any additional mechanisms to increase the power of the movement. Pre-stretch in the MTU in the shock absorption phase in drop jumps led to utilization of energy stored in tendons and muscles into heat in the take-off phase. Athletes performed the take-off in drop jumps using the technique they are accustomed to, i.e. the technique of their sport exercise. This was confirmed by a decrease in legs stiffness and an increase in mechanical power as the drop jump height increased.

5. Conclusions

The results demonstrated the strong effect of sport specialization on the motor control in elite athletes. Drop jump performed from different heights revealed peculiarities of MTU functioning which were similar to those used by athletes in competitive exercises. Thus, our data provided an important insight into the contribution of various mechanisms to generating power of a movement in top athletes from different sport disciplines. It has been determined that to achieve the maximum mechanical power in any motor action, athletes used their previous sport experience. Apparently, athletes chose a motor program that maximized the MTU potential, but they used the energy of elastic deformation stored in muscles and tendons in different ways: (1) the energy of elastic deformation permitted to obtain the maximum power due to conjoint work of muscles and tendons; (2) the energy of elastic deformation was accumulated in the tendons for its further recuperation into the muscles and their additional stretching; (3) the energy of elastic deformation dissipated with heat and the movement was performed due to muscle activation. This study confirmed the presence of two mechanisms for transferring elastic deformation energy in the lower extremities: the MTU pre-stretch mechanism and the mechanism of energy transfer via biarticular muscles. These results helped us understand how athletes of different sport specializations employed different mechanisms to increase efficiency of generation of mechanical power taking into account requirements to performance of their main sport exercise.

There were certain limitations in our work. As there were not so many elite athletes to form the experimental groups, the number of subjects in the samples was quite small. Thus, it was not possible to carry out a sufficient statistical analysis. Nevertheless, the results allowed us to define the general trend. Besides that, the work lacks experimental data related to sport exercises. Availability of such data and development of appropriate models would make it possible to expand the comparative analysis of the data. To continue this work in future, it seems important to use an individualized approach to assessing the effectiveness of each elite athlete, taking into account peculiarities of his/her sport technique. A very interesting lead for further research is modeling of conscious control of skeletal muscles and the whole body, taking into account regularities related to the use of various mechanisms of generation power of movements and behavior of MTU presented in this article.

The results of the study are useful for interpretation of differences in test jumps performed by top athletes in the course of regular control. The results of our study may help coaches choose appropriate means and methods of strength training in different sport disciplines, develop special exercises and training regimens for them.

Conflict of interest

The authors declare no conflict of interest.

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