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THE EFFECTIVENESS OF INCORPORATING INDIVIDUALIZED ISOMETRIC LOADS INTO A REHABILITATION TREATMENT PROTOCOL FOR HAMSTRING MUSCLE INJURIES IN ATHLETES: A RANDOMIZED CONTROLLED TRIAL

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Introduction. Hamstring muscle injuries are among the most common injuries in running sports. Despite the large number of existing rehabilitation approaches, there is still no universally accepted protocol that ensures optimal timing and safety for athletes' return to maximal loads.

Objective. To assess the effectiveness of an algorithmized isometric exercise protocol in the rehabilitation of highly trained athletes with hamstring injuries.

Materials and methods. The study included 30 professional athletes aged 18–29 years (17 males and 13 females; mean age: 22.9 ± 3.2 years) with an acute injury of the posterior thigh muscles (biceps femoris, semitendinosus, or semimembranosus) classified as grade 2a or 2b according to the British Athletics Muscle Injury Classification (BAMIC). Participants were randomized into two groups of 15 individuals each. Group 1 (control) received the standard basic rehabilitation protocol. Group 2 (intervention) received the basic protocol combined with the authors' algorithm of individualized isometric loads. The optimal angles of the hip and knee joints for maximal isometric contraction were determined, provided that the pain level did not exceed 3 points on the visual analogue scale (VAS). The assessments were performed using a robotic isokinetic system (Contrex). Outcomes were evaluated at weeks 3, 4, and 5 post-injury. Statistical analysis was conducted using IBM SPSS Statistics 27.

Results. The time to return to sport activity in the intervention group was 27.87 ± 4.78 days, which was statistically significantly shorter than in the control group (32.53 ± 5.22 days; $t = -2.553$, $p = 0.016$). The mean difference was 4.67 days (95% CI: -8.41 to -0.92), and the effect size was large (Cohen's $d = 0.93$). The ratio of the peak torque of the injured leg to that of the uninjured leg showed statistically significant between-group differences at all follow-up time points, favoring the intervention group. At week 3 post-injury, the values were $74.40 \pm 5.32\%$ vs. $67.53 \pm 6.29\%$ ($t = 3.230$, $p = 0.003$); the mean difference was 6.87% (95% CI: 2.51 – 11.22); the effect size was large (Cohen's $d = 1.18$). At week 4, the values were $82.47 \pm 4.73\%$ vs. $76.87 \pm 5.41\%$ ($t = 3.017$, $p = 0.005$); the mean difference was 5.60% (95% CI: 1.80 – 9.40); the effect size was large (Cohen's $d = 1.10$). At week 5 of follow-up, the ratio of the peak torque of the injured to the uninjured leg was $87.93 \pm 3.56\%$ vs. $82.60 \pm 3.52\%$ ($t = 4.128$, $p < 0.001$); the mean difference was 5.33% (95% CI: 2.69 – 7.98); the effect size was large (Cohen's $d = 1.51$).

Conclusions. The developed criterion-based protocol, supplemented with algorithmized individualized isometric training, enabled a statistically significant acceleration of recovery of symmetry in lower limb strength and reduced the time to return to sport for highly trained athletes, while maintaining a high level of safety. The obtained results substantiate the feasibility of implementing this approach in sports rehabilitation practice.

Keywords: rehabilitation treatment; rehabilitation protocol; hamstring injuries; highly trained athletes; isometric loads; return to sport

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ЭФФЕКТИВНОСТЬ ВКЛЮЧЕНИЯ ИНДИВИДУАЛИЗИРОВАННЫХ ИЗОМЕТРИЧЕСКИХ НАГРУЗОК В ПРОТОКОЛ ВОССТАНОВИТЕЛЬНОГО ЛЕЧЕНИЯ ПРИ ТРАВМАХ МЫШЦ ГРУППЫ ХАМСТРИНГ У СПОРТСМЕНОВ: РАНДОМИЗИРОВАННОЕ КОНТРОЛИРУЕМОЕ ИССЛЕДОВАНИЕ

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Введение. Повреждения мышц задней поверхности бедра относятся к числу наиболее частых травм в беговых видах спорта. Несмотря на большое количество существующих восстановительных подходов, до настоящего времени отсутствует общепринятый протокол, обеспечивающий оптимальные сроки и безопасность возвращения спортсменов к максимальным нагрузкам.

Цель. Оценка эффективности разработанного алгоритмизированного протокола применения изометрических упражнений в восстановительном лечении высококвалифицированных спортсменов с повреждениями хамстринг.

Материалы и методы. Исследование проведено с участием 30 профессиональных спортсменов 18–29 лет (17 мужчин и 13 женщин, средний возраст $22,9 \pm 3,2$ года), имевших острую травму мышц задней поверхности бедра (двуглавая мышца бедра, полусухожильная или полуперепончатая мышца) 2а или 2б степени по классификации повреждений мышц Британской атлетической ассоциации (BAMIC). Участники были рандомизированы на две группы по 15 человек. Группа 1 (сравнения) получала стандартный базовый протокол реабилитации. Группа 2 (фокусная) — базовый протокол в сочетании с авторским алгоритмом индивидуализированных изометрических нагрузок. Определяли оптимальные углы тазобедренного и коленного суставов для максимального изометрического сокращения при уровне боли не более 3 баллов по визуально-аналоговой шкале (BALL). Исследование проводилось с помощью роботизированного изокINETического комплекса Contrex. Результаты оценивали на 3, 4 и 5-й неделях после травмы. Статистическая обработка данных выполнена с использованием пакета программного обеспечения IBM SPSS Statistics 27.

Результаты. Время возвращения к спортивной деятельности в фокусной группе составило $27,87 \pm 4,78$ дня, что было статистически значимо меньше, чем в группе сравнения — $32,53 \pm 5,22$ дня ($t = -2,553$, $p = 0,016$); средняя разность составила 4,67 дня (95% ДИ: -8,41...-0,92), размер эффекта — большой (d Коэна = 0,93). Отношение пикового крутящего момента поврежденной ноги к здоровой демонстрировало статистически значимые межгрупповые различия на всех этапах наблюдения в пользу фокусной группы: на 3-й неделе с момента травмы: $74,40 \pm 5,32$ против $67,53 \pm 6,29\%$ ($t = 3,230$, $p = 0,003$); средняя разность составила 6,87% (95% ДИ: 2,51–11,22); размер эффекта — большой (d Коэна = 1,18). На 4-й неделе: $82,47 \pm 4,73$ против $76,87 \pm 5,41\%$ ($t = 3,017$, $p = 0,005$); средняя разность — 5,60% (95% ДИ: 1,80–9,40); размер эффекта — большой (d Коэна = 1,10). На 5-й неделе наблюдения отношение пикового крутящего момента поврежденной ноги к здоровой составляло $87,93 \pm 3,56$ против $82,60 \pm 3,52\%$ ($t = 4,128$, $p < 0,001$); средняя разность — 5,33% (95% ДИ: 2,69–7,98); размер эффекта — большой (d Коэна = 1,51).

Выводы. Разработанный критерияльно-ориентированный протокол, дополненный алгоритмизированными индивидуализированными изометрическими тренировками, позволил статистически значимо ускорить восстановление силовой симметрии нижних конечностей и сократить время возвращения высококвалифицированных спортсменов к спортивной деятельности при сохранении высокого уровня безопасности. Полученные результаты обосновывают целесообразность внедрения данного подхода в практику спортивной реабилитации.

Ключевые слова: восстановительное лечение; протокол восстановления; повреждения хамстринг; высококвалифицированные спортсмены; изометрические нагрузки; возврат в спорт

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INTRODUCTION

Hamstring injuries (muscle injuries of the posterior thigh) are among the most common injuries in modern sports. The high incidence, prolonged recovery period (ranging from 2 to 12 weeks), and substantial risk of recurrence (up to 30–33% within the first year after injury) make this pathology a pressing issue in sports medicine [1, 2].

Hamstring injuries are particularly common in sports requiring maximal running speed and explosive efforts, including sprinting, hurdling, jumping events in track and field, as well as football, rugby, and American football [3, 4]. The primary mechanism of injury is intense eccentric loading during the late swing phase of running at maximal acceleration, when the muscles are at their greatest length. The high vulnerability of this muscle group is due to the unique two-joint anatomy of the hamstrings (semitendinosus, semimembranosus, and the long and short heads of the biceps femoris), the combination of eccentric deceleration followed by powerful concentric contraction, and the complex coordination required among all three muscles [5–7].

Despite the high prevalence of hamstring injuries and the extensive clinical experience accumulated in global medicine, the incidence of these injuries and the recurrence rate remain high [1, 8]. These factors necessitate further study of the pathology and the development of new effective methods for rehabilitation and prevention.

The key objective for medical personnel in sports is to ensure the fastest yet safest recovery of the athlete, followed by a return to the training process that includes maximal athletic loads. Achieving this requires a delicate balance between the intensity of speed-strength exercises and the safety of the injured tissues. An overly aggressive approach risks exacerbating pain and triggering a recurrence of the injury, whereas an excessively cautious approach leads to an unnecessary loss of training and competition time, which is unacceptable in elite sports [6].

The cornerstone of rehabilitation for muscle injuries in sports is the use of criterion-based, progressively more challenging physical exercises. Timely and active loading with controlled intensity is the most effective means of stimulating recovery of muscle structure and function [7, 9].

Isometric exercises are traditionally considered the first stage of rehabilitation following musculoskeletal injuries. This is due to their safety and the possibility of initiating loading as early as the first days after the injury, provided that the load is well tolerated at a level of 2–3 points on a 10-point visual analogue scale (VAS). Isometric contractions enable early high-level activation of muscle fibres, providing strong afferent input to the central nervous system. This promotes rapid restoration of neuromuscular control and stimulates early tissue remodelling, which contributes to the recovery

of muscle architecture. Isometric exercise performed at optimal joint angles allows substantial mechanical loading of muscle fibres without changing muscle length, thereby minimizing the risk of exacerbating the injury [7, 10].

There are strong reasons to use intensive isometric exercises at all stages of rehabilitation for hamstring muscle injuries, as at certain knee and hip flexion angles, pain intensity is lower than at other angles. This is due to changes in the spatial relationship of the levers (the distance from the joint axis to the muscle's attachment point) and alterations in the tension of the muscular, fascial, and tendinous elements resulting from shifts in the spatial position of their attachment zones [2, 11].

A distinctive feature of isometric loading is the establishment and restoration of static inter-muscular coordination patterns. However, to recover speed-strength and coordination capacities of the musculoskeletal system, these exercises should be supplemented with dynamic exercises as rehabilitation progresses. At the same time, the capacity for high-level muscle fibre activation within a safe isometric regime underscores the need for further investigation into the favorable biomechanical properties of this type of exercise [12, 13].

The aim of the study was to evaluate the effectiveness of a developed algorithmic protocol for the application of isometric exercises in the rehabilitation of highly qualified athletes with hamstring injuries.

MATERIALS AND METHODS

The study included 30 professional athletes aged 18–29 years (17 men and 13 women; mean age 22.9 ± 3.2 years) who sustained an acute injury to the posterior thigh muscles (biceps femoris, semitendinosus, or semimembranosus) classified as grade 2a or 2b according to the British Athletics Muscle Injury Classification (BAMIC) [17], confirmed by magnetic resonance imaging (MRI). All participants underwent treatment at the National Center for Sports Medicine of the Federal Medical and Biological Agency of Russia.

The inclusion criteria for athletes in the study were as follows:

- age: 18–29 years;
- professional athletes: participants in national or international-level competitions, holding a sports qualification of at least Candidate Master of Sports (CMS) and competing in professional leagues/teams;
- acute hamstring injury: injury duration not exceeding 5 days at the time of treatment initiation;
- clinical and instrumental confirmation of a grade 2a (myofascial involvement) or 2b (musculotendinous junction injury) muscle injury according to the British Athletics Muscle Injury Classification (BAMIC) [17];
- written informed consent to participate in the study and willingness to adhere to the study protocol.

The exclusion criteria for athletes were as follows:

- muscle injury grade 2c (moderate intratendinous lesion) or grades 1, 3, and 4 according to the British Athletics Muscle Injury Classification (BAMIC);
- injury duration exceeding 5 days;
- chronic or recurrent hamstring injuries;
- age outside the inclusion range (≤ 18 or ≥ 30 years);
- lack of formal sports qualification;
- concomitant injuries (e.g., ligament ruptures in the knee or hip joint, fractures, injuries to other muscles, etc.);
- presence of systemic diseases affecting tissue regeneration processes;
- refusal to participate or non-compliance with the rehabilitation protocol.

In this study, the effectiveness of the applied method was assessed by the time to return to sports-specific training loads. Therefore, the following criteria were selected as key benchmarks to comprehensively and safely confirm the athlete's readiness to resume the baseline activity level: pain-free running at maximum speed, including directional changes; isokinetic strength test results for the hamstring, quadriceps, and gluteal muscle groups at least 80% of the contralateral limb, without pain; jump tests with performance at least 80% of the contralateral side, without pain; restoration of symmetry in stability indicators (SSI): Y-balance test symmetry $\geq 90\%$, single-leg stance duration > 30 s, Pallof press hold > 30 s, single-leg glute bridge with marching > 30 s; the athlete's self-assessment of full readiness for sports loads, evaluated using questionnaires (TSK-11, I-PRRS, SCI, etc.).

Block randomization was used to allocate athletes to groups. The block size was 6 participants (3 participants per group). This method was selected due to the prospective nature of the study and the gradual enrolment of participants over several years, which required maintaining an approximately equal group size throughout the recruitment period. The sequence of blocks was pre-generated using a random number generator¹. Each new athlete who met the study's inclusion criteria was sequentially assigned to a group according to the next

position in the current block. Once a block was filled, a new block automatically began. This approach ensured a balanced distribution of participants across groups regardless of their enrolment time and minimized the risk of selection bias.

Athletes were divided into two observation groups:

- Group 1 (control group; 9 men and 6 women; mean age 22.9 ± 3.3 years; Shapiro–Wilk test value: 0.796, indicating a normal distribution), $n = 15$ — athletes who received the standard rehabilitation protocol [11, 14–16];
- Group 2 (focus group; 8 men and 7 women; mean age 23.0 ± 3.4 years; Shapiro–Wilk test value: 0.778, indicating a normal distribution) — the standard rehabilitation protocol plus isokinetic training with maximal loads at effective angles, provided that pain was confidently controlled.

The distribution of athletes by body mass index (BMI) was comparable between the two groups and fell within the range of 19.6–24.7 kg/m² (mean BMI 22.2 ± 1.4 kg/m²), which corresponds to normal values for athletes in speed-strength sports. The mean BMI in Group 1 was 22.1 ± 1.3 kg/m² (Shapiro–Wilk test: 0.553, indicating a normal distribution), while in Group 2 it was 22.3 ± 1.5 kg/m² (Shapiro–Wilk test: 0.894, indicating a normal distribution). No statistically significant differences in this parameter were found between the groups ($p = 0.77$). The comparability of the groups in terms of BMI was important because this parameter directly affects the magnitude of mechanical load on the posterior thigh (hamstring) muscles during running and jumping movements, as well as the overall lower limb biomechanics. Thus, ensuring BMI comparability between the groups allowed us to minimize this confounder and increase the reliability of the effectiveness assessment of the isometric protocol. The characteristics of the groups are summarized in the table.

The distribution of athletes by sex across the groups was compared using Fisher's exact test. No statistically significant differences in this parameter were found between the intervention and control groups ($p = 0.5$). The groups also showed no statistically significant

Table. Comparability of the study groups ($M \pm SD$)

Parameter	Group 1 (control group) $n = 15$	Group 2 (intervention group) $n = 15$	Significance level, p
Age, years	22.9 ± 3.3	23.0 ± 3.4	0.91
Body mass index, kg/m ²	22.1 ± 1.3	22.3 ± 1.5	0.77
Males, abs. n. (%)	9 (60)	8 (53.3)	0.5
Females, abs. n. (%)	6 (40)	7 (46.7)	

Table prepared by the authors based on their own data

Note. $M \pm SD$ — arithmetic mean and standard deviation; n — athlete count per group.

¹ RANDOM.ORG. True Random Number Service. URL: <https://www.random.org/>

differences in age ($p = 0.91$). In both observation groups, athletes representing various sports (football, track and field sprint disciplines, rugby, American football) were comparable in terms of sports qualification level and the time elapsed from injury to the start of treatment.

The domestic clinical guidelines “Closed Soft Tissue Injuries of the Limbs”² do not include a staged treatment protocol for proximal hamstring injuries that would be applicable to the rehabilitation of professional athletes. For this reason, we developed a criterion-based, phase-based rehabilitation protocol that includes all necessary types of physical loads. The protocol is grounded in the evidence from sports medicine regarding the most effective individual exercises and comprehensive rehabilitation protocols, including POLICE, PEACE & LOVE, Askling’s L-protocol, the Nordic Hamstring (NH) exercise, the Aspetar Hamstring Protocol, and the London International Consensus on Hamstring Injury [11, 14–16]. The protocol is divided into 3 phases: the acute period (inflammatory phase), the subacute period (regenerative phase), and the functional period (remodeling phase).

In the search for new effective methods for hamstring injury rehabilitation, we have developed and implemented an algorithmized, individualized rehabilitation protocol. The protocol employs gradually increasing isometric loads, with mandatory regular assessment of the most effective knee and hip joint positions in which hamstring contraction force is maximal, provided that pain is confidently controlled. Based on current international research, exercise loads with a pain threshold of up to 2–3 points on the 10-point VAS are considered the most effective for rehabilitation during the subacute and functional phases [8, 11]. Given the lowest injury risk associated with isometric loading compared to other types of exercise, a pain level of 3 points on the VAS was adopted as the threshold value for this type of exercise in the present study.

Due to the nature of the intervention (additional isometric exercises in the intervention group), blinding of study participants and the researchers directly conducting the sessions was not performed. Blinding was also not applied during the assessment of primary outcomes (isokinetic testing), as all measurements were carried out by the same certified specialist.

Once a week, athletes in the intervention group performed a series of maximal isometric hamstring contractions under pain control in various knee and hip joint positions, during which the generated force was recorded. The optimal knee flexion angle was determined sequentially by testing angles of 10°, 30°, 50°, 70°, and 90°. Two positions were used to determine the optimal hip joint angle: prone position with 0° flexion and sitting in a chair with 80° flexion. Thus, the angles were selected based on the athlete’s ability to generate the maximum

possible force while maintaining the established pain threshold. Maximal isometric hamstring contractions were performed at these specific angles within the pain threshold (≤ 3 points on the 10-point VAS). The protocol included 3 sets of 10–15 maximal contractions, each lasting 10–30 s, with the duration and intensity adjusted according to the athlete’s recovery progress. The exercises were performed 5 times per week, with a 30-s rest interval between repetitions (Fig. 1).

Protocol adherence in the intervention group was monitored through training diaries and weekly in-person checks by a specialist.

The optimal angles were determined using the Contrex robotic system (Physio SA, Switzerland). The use of such a robotic isokinetic system in research offers several advantages over manual dynamometry: high accuracy and reproducibility of hip and knee joint positioning (accurate to 1°); elimination of the influence of the examiner’s strength and fatigue, thereby ensuring objectivity and standardization of measurements when working with highly trained athletes who possess considerable muscle strength; the ability to generate a complete angle–torque curve in real time across the full available range of motion, which allows precise identification of the most effective isometric loading angles for each specific rehabilitation session; instant feedback and automatic load limitation, which significantly

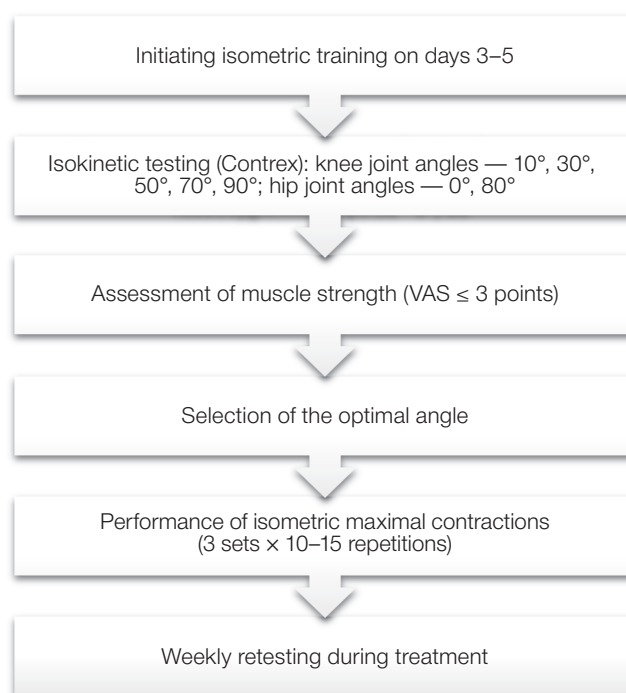


Figure prepared by the authors based on their own data

Fig. 1. Algorithm for determining optimal angles for individualized isometric loading using the Contrex isokinetic system

² Ministry of Health of the Russian Federation. Clinical Guidelines: Closed Soft Tissue Injuries of the Limbs. Moscow; 2024. URL: <https://legalacts.ru/doc/klinicheskie-rekomendatsii-zakrytye-povrezhdeniya-mjagkikh-tkanei-konechnostei-odobreny-minzdravom/>

enhance procedure safety when operating near the pain threshold (≤ 3 points on the VAS); and an adjustable chair-table with limb supports and ergonomic restraints for the trunk and limbs.

All athletes underwent staged isokinetic testing of hamstring strength under pain control (within 2–3 points on the VAS) in the eccentric mode at an angular velocity of 60°/s in a seated position. In this study, test results were evaluated at 3, 4, and 5 weeks after the injury. Athletes who completed the treatment earlier underwent repeat testing after being cleared to return to sport. Further staged testing was performed in a subset of athletes who continued treatment for more than 5 weeks. The data presented in this study are limited to the first 5 weeks, as beyond this time point, due to the travelling nature of training and competition activities, some athletes who had been cleared to return to sport were located in other regions of the country and could not participate in further testing.

Statistical data processing was performed using the IBM SPSS Statistics 27 software package. Intergroup differences were assessed using the independent Student's *t*-test. No statistically significant differences between the groups in terms of baseline characteristics were found ($p > 0.05$). Treatment was administered under the supervision of certified rehabilitation specialists (trauma and orthopedic surgeon, physical therapy physician, and physical therapy instructor-methodologist) using modern equipment.

RESULTS AND DISCUSSION

During the study, a statistically significant intergroup difference was found for the time to return to training (time

to return to sport) ($t = -2.553$; $p = 0.016$). In the intervention group, where athletes additionally underwent isokinetic training, a statistically significant reduction in the time to return to the standard training process was observed: 27.87 ± 4.78 days versus 32.53 ± 5.22 days ($p = 0.016$). The mean difference in time was 4.67 days (95% CI: -8.41 to -0.92); the effect size was large (Cohen's $d = 0.93$). In all cases, Levene's test for equality of variances did not reveal statistically significant differences between the groups ($p > 0.05$) for all studied parameters; therefore, the analysis variant assuming equal variances was used.

The recovery dynamics of hamstring strength were assessed by evaluating the ratio of the torque produced on the injured side to that of the contralateral side at weeks 3, 4, and 5 post-injury. Isokinetic testing was performed in the eccentric mode at an angular velocity of 60°/s using the Con-Trex robotic system. Load-strength testing was performed starting from week 3 after the injury, since in the earlier periods, isometric strength testing provides little informative value for most athletes due to the difficulty in controlling the pain threshold.

It was found that the ratio of the peak torque of the injured leg to that of the healthy leg showed statistically significant intergroup differences at all follow-up stages, favoring the focus group (Fig. 2). Specifically, at 3 weeks post-injury, this parameter was $74.40 \pm 5.32\%$ in the focus group versus $67.53 \pm 6.29\%$ in the control group ($t = 3.230$, $p = 0.003$). The mean intergroup difference was 6.87% (95% CI: 2.51–11.22), and the effect size was assessed as large (Cohen's $d = 1.18$). At 4 weeks post-injury, the peak torque ratio (injured/healthy leg) was $82.47 \pm 4.73\%$ in the focus group versus $76.87 \pm 5.41\%$ in the control group ($t = 3.017$, $p = 0.005$); the mean difference was 5.60% (95% CI: 1.80–9.40), with a large effect size (Cohen's $d = 1.10$). At 5 weeks post-injury, the values were $87.93 \pm 3.56\%$ and $82.60 \pm 3.52\%$, respectively ($t = 4.128$, $p < 0.001$); the mean difference amounted to 5.33% (95% CI: 2.69–7.98), and the effect size was again large (Cohen's $d = 1.51$).

The obtained results are consistent with data from other studies confirming the effectiveness of isometric exercises in hamstring injury rehabilitation [1, 8, 11, 15]. However, in most previous studies, isometric exercises were performed at fixed, standard angles without individualized selection of optimal positions [1, 5, 14–16]. The present study addresses this gap by demonstrating the advantages of individualized selection of optimal angles for isometric exercises.

In the present study, an algorithm for individualized selection of optimal knee and hip joint angles was applied to the focus group. This allowed athletes to perform isometric contractions in the most effective positions for each individual, with pain monitored, which likely contributed to better outcomes in terms of return-to-sport time and recovery of strength parameters.

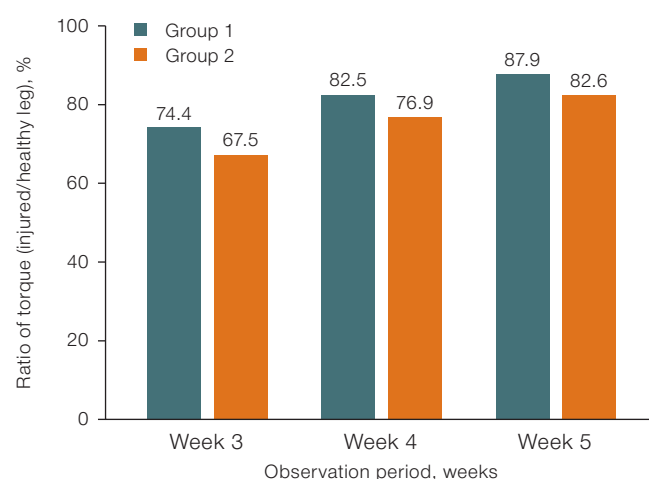


Figure prepared by the authors based on their own data

Fig. 2. Dynamics of recovery of the peak torque of the injured limb relative to that of the healthy limb during rehabilitation, assessed by isokinetic testing (60°/s, eccentric mode). Group 1 — intervention group; Group 2 — control group. Statistically significant differences were observed ($p \leq 0.005$)

The study had several limitations: a relatively small sample size ($n = 30$), lack of long-term follow-up to monitor injury recurrences after return to sport, and inclusion of only athletes with grade 2a and 2b hamstring muscle injuries according to the BAMIC classification. Further studies with larger sample sizes and longer follow-up periods will help to refine and expand the obtained data.

CONCLUSION

The results of the study demonstrated that incorporating algorithmized isometric exercises into a criterion-based protocol contributed to a statistically significant acceleration of recovery of symmetry in lower limb strength at all observation stages (from week 3 to week 5) and to a reduction in return-to-sport time. Athletes in the focus group demonstrated higher ratios of the peak torque of the injured leg to that of the healthy leg and returned to sport on average 4.7 days earlier compared to the control group.

The staged, criterion-based protocol developed at the National Center for Sports Medicine, which includes algorithmized isometric training, complements the standard rehabilitation protocol and is adapted to the needs of highly trained athletes.

A key feature of the proposed method is its universality: maximal isometric contractions are applied

according to a single principle at all stages of the treatment process. Only the limb position and the magnitude of external resistance are adjusted (depending on the athlete's current capabilities), while the core principle — “maximal effort with strict pain control” — remains unchanged. Another advantage of this technique is its simplicity. Complex equipment is not required for testing; a mechanical dynamometer is sufficient. These conditions help to maintain a high level of neuromuscular activation continuously, prevent atrophy, restore muscle mass and strength, and gradually expand the pain-free range of motion. Adding this technique to the criterion-based, staged rehabilitation protocol we developed preserves all the benefits of the evidence-based recovery approaches included in it while enhancing the neuromuscular component of rehabilitation. This is expected to lead to a more robust and sustainable functional outcome in athletes with hamstring muscle injuries of varying severity.

Further prospective randomized studies with larger sample sizes will help to more precisely determine the optimal parameters of isometric loading and its role within modern rehabilitation protocols.

The study findings can be applied in the practice of sports medicine physicians, physical therapy specialists, and traumatologists to optimize rehabilitation programs for hamstring muscle injuries.

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