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REVIEW ARTICLE

Training Transfer: Scientific Background and Insights for Practical Application

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Abstract Training transfer as an enduring, multilateral, and practically important problem encompasses a large body of research findings and experience, which characterize the process by which improving performance in certain exercises/tasks can affect the performance in alternative exercises or motor tasks. This problem is of paramount importance for the theory of training and for all aspects of its application in practice. Ultimately, training transfer determines how useful or useless each given exercise is for the targeted athletic performance. The methodological background of training transfer encompasses basic concepts related to transfer modality, i.e., positive, neutral, and negative; the generalization of training responses and their persistence over time; factors affecting training transfer such as personality, motivation, social environment, etc. Training transfer in sport is clearly differentiated with regard to the enhancement of motor skills and the development of motor abilities. The studies of bilateral skill transfer have shown cross-transfer effects following one-limb training associated with neural adaptations at cortical, subcortical, spinal, and segmental levels. Implementation of advanced sport technologies such as motor imagery, biofeedback, and exercising in artificial environments can facilitate and reinforce training transfer from appropriate motor tasks to targeted athletic performance. Training transfer of motor abilities has been studied with regard to contralateral effects following one limb training, cross-transfer induced by arm or leg training, the impact of strength/power training on the preparedness of endurance athletes, and the impact of endurance workloads on strength/power performance. The extensive research findings characterizing the interactions of these workloads have shown positive transfer, or its absence, depending on whether the combinations conform to sport-specific demands and physiological adaptations. Finally, cross-training as a form of concurrent exercising in different athletic disciplines has been examined in reference to the enhancement of general fitness, the preparation of recreational athletes, and the preparation of athletes for multi-sport activities such as triathlon, duathlon, etc.

1 Background

Training transfer as a scientific and important practical multidisciplinary problem has been extensively studied in physiology, applied psychology, management theory, and industrial education. Its history traces back more than 100 years to the classical publication of Thorndike and Woodworth [1], who conceptualized the problem and predicted its main directions for further development. The original definition postulates that transfer is characterized as the extent to which a response in one task or trained situation affects the response in another task or untrained situation [2]. The importance of this problem is underlined by its financial implications: according to findings of the American Society for Training and Development, the annual outlay of US organizations in the professional training of employees in 2003–2005 exceeded US$125 billion [3].

With more than 100 years of investigation, training transfer can be considered the key problem of contemporary sport and theories of athletic training. Because of its close connection with essential issues of exercise physiology, psychology, biomechanics, and theory of learning, training transfer constitutes the methodological basis for

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implementing advanced athletic training technologies, coaching concepts, and general know-how. Indeed, each training system in any sport involves the execution of event-specific exercises and auxiliary drills intended to enhance motor fitness and/or technical skills in that given sport. Moreover, even event-specific drill settings usually contain a number of specially designed exercises whose biomechanical and neuro-coordinative patterns substantially differ from competitive performance. It is commonly believed that such modified exercises produce a positive effect on competitive performance despite their differences from the targeted discipline. In terms of training theory this expectation is based on the suggestion that these exercises enable positive training transfer to competitive performance. These expectations are not always reasonable. This review intends to summarize current knowledge on training transfer and to propose several approaches for applying this knowledge to practice. Its content is based on evidence, facts, and concepts drawn mainly from peer-reviewed journals publications using Google Scholar search engines, SIRC, MEDLINE, and the PubMed electronic database. The publications, including several books, were selected to characterize historical, current, and updated aspects of the issue under consideration.

Apparently the initial stimulus for investigating training transfer was associated with industrial/organizational needs [4]. The next section presents basic concepts of general theory and major factors affecting training transfer.

1.1 Basic Concepts of Training Transfer

The general theory of transfer distinguishes between positive, negative, and zero transfer [5]. Positive transfer is defined as the degree to which trainees succeed in increasing the level of skills and abilities they apply in their job as the result of the training they have undergone. Correspondingly, negative transfer can be observed when training interferes with professional skills, and "zero" transfer is a situation in which the impact of training is nil.

Thorndike and Woodworth [1], who were the pioneers in the study of training transfer, proposed the concept of generalization of responses when the methods, approaches, and stimuli used for the learning task are similar to those in the targeted task. Afterwards, a differentiation was proposed between *near transfer tasks*, when the degree of similarity to targeted task is high; and *far transfer tasks*, in which conditions and situations are quite different from the targeted settings. The important outcome of the generalization process is the ability to react appropriately to a new situation because of its similarity to a familiar one [4].

The idea of transfer is also interpreted and supported through a concept that includes two major dimensions:

Generalization, which presupposes that knowledge, skills, and abilities acquired in learning and training settings can be applied to different settings and situations
Maintenance, which means that outcomes of learning and training persist over time [6]

A further consideration of the generalization process differentiates between *lateral* and *vertical transfer* [5]. The first occurs when the outcomes of training process can be utilized in a wide spectrum of tasks and situations of similar complexity and difficulty as the previous settings. Vertical transfer occurs when acquired skills and abilities are exploited for the acquisition of more difficult and complex skills, which allow trainees to achieve a higher level of competence [6].

1.2 Factors Affecting Training Transfer

Considering the most relevant factors involved in transfer has traditionally been the focus of training transfer experts [4, 7]. The most commonly examined and categorized factors are clustered in three groups: individual, motivational, and environmental factors [8]. A large body of studies has undertaken to evaluate the effects of these factors on the transfer of training (Table 1).

Individual factors encompass essential personality characteristics such as locus of control, which reflects the general extent to which individuals expect that their own activity controls training outcomes such as potential rewards and reinforcements in life. Similarly, self-efficacy as an individual factor also affects training transfer. In the long run, those persons with higher confidence will be more efficient in applying newly acquired skills and abilities.

Motivational factors such as career and job attitudes, organizational commitment, decision-making and reaction to training, and post-training interventions generally refer to individuals' cognitive state, belief in and acceptance of training goals, willingness to take part in training decisions, and readiness to adopt and maintain training results.

Finally, environmental factors have a substantial impact on the efficacy of training and training transfer. Indeed, a transfer climate and a continuous-learning culture, which are closely connected with social support and cultural background, strongly determine the shape and success of the training process itself and of post-training behaviors and initiatives.

Certainly, not all elements of training transfer proposed and promoted in management theory can be adopted in their entirety in sport training. However, their creative interpretation can make a valuable contribution in both the science and practice of athletic preparation.

Table 1 Summary of publications considering the factors affecting training transfer in management and professional education

Group of factors	Content	Comments	Sources
Individual	Locus of control	Strong belief among trainees that they can control and facilitate the application of training outcomes in their job	Tziner et al. [9]
	Self-efficacy	Trainees with high confidence in training anticipate the transfer of newly acquired skills and abilities	Bandura [10]
Motivational	Career/job attitudes	Level of career/job attitudes affects readiness to learn and refine current skills and knowledge	Facteau et al. [11]
	Organizational commitment	Acceptance of training goals and willingness to exert work efforts and desire to maintain organizational membership	Tannenbaum et al. [12]
	Decision/reaction to training	Trainees who are able to provide input into the training decision perceive higher usefulness of the training for their job	Baldwin and Ford [4]
	Post-training interventions	Post-training feedback and performance-oriented interventions positively affect the trainees' ability to transfer training outcomes	Cheng and Ho [8]
Environmental	Transfer climate	Transfer climate consists of *situational cues* such as manager goals, peer support, equipment	Roulillier and Goldstein [13]
	Continuous learning culture		Blume et al. [7]
	Task constraints	Adequate and reasonable modification of post-training behaviors working in continuous-learning environment	Tracey et al. [14]

2 Training Transfer in Sport Science and Practice: Importance and Limitations

The general situation regarding training transfer in the preparation of athletes seems rather paradoxical: training transfer as a phenomenon is extensively exploited in practical routines although it is much less studied and valued than in other branches of professional and industrial education. At the same time, both scientifically and practically the importance of training transfer in the preparation of athletes cannot be underestimated.

2.1 Training Transfer as a Major Contributor Determining the Effect of Athletic Training

According to the fundamentals of exercise and sport physiology, the training effects occur as a result of the overload principle which claims that *fitness gains require a load (stimulus) magnitude that exceeds the accustomed level* [15]. According to Zatsiorsky [15] load magnitude can be properly regulated by varying its three components: training intensity, training volume, and novelty of exercises. Training load specificity is characterized by the transfer of training results from one task (auxiliary exercise) to another task (main exercise). Normally coaches employ a wide abundance of exercises, most of which can be divided into two groups:

Exercises to improve motor abilities (strength, endurance, etc.)
Exercises to improve technical skills

In both cases, the usefulness of each exercise depends on how it affects the main (competitive) performance. In other words, the transfer of motor abilities and of technical skills from training routines to competitive performance determines how useful these auxiliary drills are.

Two important features of training transfer are of particular interest: The transfer of technical skills is much more restricted than the transfer of motor abilities [15, 16]; both are highly dependent on athletes' qualifications. Low- and medium-level athletes are more sensitive to any kind of training stimuli, including non-specific ones, whereas training transfer among high-performance athletes is strongly restricted by the specificity of auxiliary exercises [17].

It is worth noting that problems of training transfer can be avoided by using competitive exercises exclusively and simply manipulating their volume and intensity. Apparently this tactic leads to a pronounced increase in energy expenditure, emotional tension, and fatigue; in this case athletes quickly approach the upper limits of their biological adaptation and the problem of training transfer is replaced by the problem of overtraining. Therefore, varying and innovating routine exercises and enriching the content of training exercises are desirable means of increasing training stimulation.

The problem of training transfer is closely connected with *learning transfer*, which can be defined as "the effect that learning one skill has on the subsequent learning of another skill" [18]. Motor learning and further perfection of motor skills constitute the content of technical preparation, which is an indispensable part of training in any sport. Another no less important aspect of training pertains to physical preparation, which is intended to enhance motor abilities (e.g., strength, endurance, speed, and agility). It is obvious that the physiological background, methods, training forms, and coaching approaches to improving technical skills and motor (physical) abilities are very different. Consequently, the training transfer of technical skills and motor abilities will be considered separately.

2.2 Training Transfer Viewed Practically

Manipulating training volume and intensity has always been the focus of training analysts [19–21], whereas the search for new exercises and tasks that produce a more pronounced training response has been the prerogative of creative practitioners. The problem of exercise novelty is linked to the rigid limitations of training transfer that from the outset determine the usefulness of specific exercises/tasks for a targeted skill or ability. Indeed, it is no problem to find exercises that athletes are unfamiliar with. The problem is to locate or create a new exercise that corresponds to the demands of specificity that dictate competitive performance. These limitations deriving from the particularities of training transfer strongly restrict the introduction of new drills to enhance motor abilities and/or technical skills.

A salient example of the successful manipulation of exercise settings can be found in the long-term experience and publications of Dr. Bondarchuk [22, 23], a world-known expert in athletic training. His concept involves the selection and implementation of separate sets of specific and semi-specific exercises, whose content is restructured from one stage to the next of annual preparation. Such program modification maintains the athletes' higher sensitivity to renewed stimuli, which meets the demands of positive training transfer. As a consequence, athletes achieve magnificent results whereas the total volume of workloads is even less than in the traditional approach to training. The outcomes of this experience are extremely impressive: in two Olympic Games (1988 and 1992) all the athletes on the podium for medals in hammer throw (gold, silver, and bronze) were coached by Bondarchuk.

It is obvious that training transfer is similarly important for both individual and team sports, where unpredictable game situations dictate skills above the demand for transferability of tactical skills.

Summarizing, training transfer can be described as the key problem of contemporary sport, one that is equal in importance to theoretical background and the aggregation of practical guidelines.

3 Transfer of Technical Skills

The principal factor limiting technical skill transfer is the neuromuscular specificity involved in each sport-specific movement technique. To maximize positive transfer of skill, an exercise should thoroughly correspond to sport-specific coordination demands. This is why a relatively narrow circle of exercises provides positive transfer to movement technique preparedness.

3.1 Bilateral Skill Transfer

For more than 100 years [24, 25] bilateral skill transfer—the impact of training a limb from one side of the body on the corresponding limb on the other side of the body—has been studied and exploited in motor learning. Positive training transfer following unilateral movement exercising occurs in various motor skills, especially where mirror-image movements are particularly popular for examination [25, 26]. It is known that training transfer between bilateral links (i.e., arms and legs) is more pronounced than between ipsilateral (same side) and diagonal arm and leg body links [27].

It was generally assumed that bilateral transfer of motor skills increases with the age of learners. Indeed, examination of 96 girls aged 7–17 years, performing a rotary pursuit tracking task revealed greater bilateral transfer in older girls as compared with their younger counterparts [28]. An older population of males and females was studied using a mirror tracking task, where the initial and final trials were performed with their non-preferred hand whereas training was done with their preferred hand [29]. Comparison of the early adult group (19–39 years) with the middle adult group (40–65 years) revealed no difference in bilateral transfer with regard to performance time, but did reveal a difference in accuracy. The older trainees had lower initial levels of performance accuracy which increased to a higher extent than among the younger subjects.

The gender effect was studied in adult trainees and females were found to be superior to males in accuracy and performance time in mirror-tracing tasks [30]. However, a later study with adult subjects did not support these findings; males performed the tasks with lower accuracy, but they recorded shorter performance time than the females [29]. A similar study conducted with 160 girls and boys aged 6–12 years revealed the opposite gender effect; boys achieved greater bilateral transfer of ball throwing accuracy than girls [31, 32]. This discrepancy in study outcomes in adult and children populations can be partly explained by the different motor tasks used in the various studies.

One more issue of relevance concerns differences in bilateral transfer from the preferred to non-preferred side and vice versa. It is commonly believed that the limbs of the preferred side are involved in most motor activities and therefore have greater transfer effect on the limbs of the non-preferred side [27]. The findings of recent studies do not support this assumption. These studies reported more pronounced transfer from the non-preferred to the preferred arm as compared to the opposite direction [32, 33]. This effect was noted for both left- and right-handed trainees [27, 34].

Although the mechanism of bilateral motor skill transfer is still unclear, the basic explanations of this phenomenon pertain to central and peripheral neural regulation, mental practice, and cognitive functions. It is suggested that the performance of a motor task by a unilateral limb causes changes in cortical areas associated with motor command, activation of the hemisphere contralateral to the exercised limb, and changes at the motor neuron level on the non-exercising side [35, 36]. Furthermore, the afferent input associated with the performance of a voluntary motor task could exert crossed effects at cortical, subcortical, propriospinal, and segmental levels [37, 38].

It is noteworthy that the technical mastery of various sports contains many motor skills of an asymmetrical movement structure, such as dribbling, shooting in ball games, etc. Knowledge about bilateral transfer can contribute to the development of programs that help to enhance technical mastery by employing exercises directed to the limbs of the preferred and/or non-preferred sides.

3.2 Use of Biofeedback

One more option for reinforcing the training effect while acquiring new motor skill and refining movement technique entails the use of biofeedback during different exercises and/or within separate sessions. The term “biofeedback” refers to external physiological, biomechanical, or psychophysiological feedback that is intended to provide athletes with information that can assist them to perform movement more efficiently. One of the pioneers of the biofeedback studies, Dr. Basmajian [39], used electromyography (EMG) feedback to imbue subjects with voluntary control over the discharge of single motor units. This salient example spurred interest among sport researchers and since then many biofeedback studies have been conducted in sport and physical education. In recent decades innovative projects have been carried out in two main directions:

Enhancement of motor control and movement technique during performance using real-time feedback of muscular activity and/or motor output

Improvement of motor performance by means of directed biofeedback training in separate sessions to enhance neuromuscular and biomechanical responses, which can be utilized during subsequent athletic practices

The first direction has various applications, mostly in individual sports, and usually leads to a significant increase in movement effectiveness. A number of research projects tried to enhance movement technique based on EMG feedback, where athletes were requested to modify their movement coordination and follow appropriate patterns of neuromuscular activity. This approach was successfully implemented for optimizing the movement structure of canoe/kayak paddlers [40, 41], as well as for optimizing agonist/antagonist interactions in ballistic throwing movements [42]. Biomechanical feedback was effectively used to enhance the dynamic reactions of cyclists during pedaling [43]. A similar approach has been implemented in swimming, where athletes were provided with real-time information on the magnitude of propulsive force generated by the hands [44]. The further development of contemporary sport technologies has resulted in the proliferation of feedback systems in rowing and canoeing [45]. As a result, the practice of canoe/kayak paddlers and rowers around the world includes abundant exercises with on-line programming of stroke rate and velocity regimes. A similar tendency can be seen in other endurance sports such as cycling, skiing, skating, and running.

The second direction contains various applications for biofeedback training for gaining voluntary control over “involuntary” psychophysiological responses, using appropriate equipment and/or laboratory settings [46]. This approach was exploited initially for the treatment of health-related disorders; however, further modifications of the method led to the elaboration of several sport-specific protocols, where movement technique and motor performance became a matter of conscious regulation and optimization. Specifically, biofeedback training entailing the voluntary control of selected physiological characteristics such as EMG, galvanic skin response (GSR), heart rate, etc., made it possible to enhance motor performance and movement patterns in various athletic disciplines, such as gymnastics [47], shooting [48], kayaking [49], and swimming [50]. Although the biofeedback interventions did not immediately affect the biomechanical patterns of the athletic performances under study, their positive impact on relevant sport-specific technical characteristics has been repeatedly shown in studies.

Summarizing the data on biofeedback, it can be assumed that implementation of on-line biofeedback correction of movements helps to increase training transfer from these exercises to targeted performance and can be characterized as a valuable option for attaining more efficient athletic preparation. Conducting separate biofeedback sessions to target selected motor tasks in order to improve sport-specific sensory-motor reactions and neuromuscular regulation also has a positive effect on targeted athletic performances, although training transfer in these cases may require additional transformation and may be delayed. A clear association between biofeedback training in laboratory settings and enhanced performance patterns needs additional experimental support. In any case biofeedback interventions have great potential for increasing training transfer in motor learning and in perfecting movement technique.

3.3 Use of Imagery

Imagery is probably the most widely recognized and extensively used instrument for facilitating, enhancing, and diversifying athletic preparation. Although motor imagery is used for various purposes its potential to make motor learning more effective and to perfect technical skills has drawn particular interest from both researchers and practitioners. It has been established that motor imagery combined with physical rehearsal shows significantly greater bilateral transfer relative to a control condition [51]. It has been proposed that the proprioceptive feedback elicited by imagery serves as the underlying mechanism whereas cognitive operations create the basis for motor performance [52]. Moreover, it has been shown that if brain activity during imagery is very similar to such activity during physical performance, skill transfer to the contralateral limb is much greater [53].

There are many definitions that emphasize different aspects of imagery; one of the most comprehensive and laconic was offered by Vealey and Greenleaf [54]: "Imagery may be defined as using all the senses to re-create or create an experience in mind" (p. 1). Sports psychology experts differentiate between imagery ability and imagery use. The first one is usually understood as the individual's capacity to form and maintain vivid and controllable images, whereas the second is considered the manner in which athletes actually image themselves in order to facilitate and enhance technical skills and motor performance [55]. The formation of vivid and realistic images of motor performance presupposes the activation and utilization of various senses such as sight, sound, kinesthetic feelings, and smell, which occur during real performance. To this end detailed scripts as well as visual and acoustic materials are used and recommended for practical settings.

A general assumption that has repeatedly been supported by research findings is that imagery enhances physical performance during new motor skill acquisition, helps refine movement technique in experienced athletes, and corrects errors in low-, medium-, and high-level athletes. In all these cases a combination of physical and mental practice is usually considered important and highly desirable because together they provide beneficial performance enhancement as compared with physical practice alone [56, 57].

Various theories attempt to elucidate the ergogenic effect of motor imagery, focusing on philosophical, motivational, cognitive, and bioinformational aspects of the process. The most promising explanation of this phenomenon proposes a theory of functional equivalence between the mental imaging of a movement and its motor performance. This theory is based on evidence that mental imagery elicits cortical activation that closely resembles the neural pattern which occurs during execution of the imagined action [58]. Further in-depth analyses have revealed a similarity between the neural patterns associated with activation of the supplemental motor cortex [59], the cerebellar contribution to imagery, and even activation of the primary motor cortex, although to a lesser extent than in motor execution [60].

On the basis of the theory of functional equivalence one should expect a pronounced impact of imagery on motor performance even without the support of practical exercising. In fact, however, study designs in which athletes executed imagery-only programs had a negligible impact on motor performance [61–63]. At the same time many well-controlled studies have shown a significant superiority of training programs in which physical and mental practices were performed in reasonable combinations [55]. Exceptions were found in cases of injured athletes who practiced imagery as part of their rehabilitation program [64]. Therefore, it can be assumed that motor imagery as part of the entire preparation program does not directly affect motor performance but rather facilitates and reinforces training transfer from appropriate motor learning and/or technical exercising executed by athletes. This function of imagery as a way to enhance training transfer appears to be very important for athlete preparation and no less important from an exercise physiology viewpoint.

3.4 Use of Artificial Environment

An artificial environment (AE) in the context of this review can be defined as a man-made environment that simulates a real-world setting, emphasizing specially selected demands and controllable conditions. The experience of creating and utilizing such systems has led to the development of specialized testing devices which simulate various outdoor athletic activities such as running, cycling, rowing, canoeing, skiing, skating, and sailing in laboratory settings [65]. Further modifications of these technologies, which have become more controllable and open to correction, have led to greater biomechanical similarity between the modeled and real technical performances. The employment of such artificial biotechnical systems has been used for refining technical skills. It was assumed, and has repeatedly been supported by empirical results, that training transfer from such exercising is more beneficial than when traditional technical drills are used.

Recent breakthroughs in computer technologies have led to the development of virtual reality training systems whose effectiveness has been demonstrated in the professional training of pilots, surgeons [66], drivers [67], and parachutists [68]. It can be suggested that virtual reality has serious limitations in sport practice owing to its lack of the motor component, which is extremely important for movement technique enhancement. To date, a number of research projects have been conducted in the virtual environment; their outcomes have identified optimal neuromuscular parameters for vertical jump [69], verified the mechanical demands for take-off in ski jumping [70], and determined the basic kinematic parameters for lower-extremity training [71]. Another proposed application of virtual reality has been to examine anticipatory performance of experienced and novice tennis players by means of computationally simulated serve motion [72]. To be sure, evaluating the training transfer produced during exercise with a virtual environment seems rather difficult, although a certain positive impact can be expected with regard to didactic and cognitive requirements.

In recent decades a number of research projects have been conducted using artificial training environments created by a mechanical simulator coupled with a computer-based interactive virtual environment. This innovative approach has provided enormous opportunities to explore and correct human movements in conditions equivalent to high-level real performance. These advanced technologies have been implemented in several Olympic sports such as sailing, bobsled, and rowing.

The sailing simulator consisted of a mechanically driven deck and computerized system that realistically reproduced sport-specific technical demands whose implementation was evaluated as the technical abilities of competitive helmsmen were perfected. Study outcomes revealed a high level of similarity between simulated and real activities [73]. The bobsled simulator was also designed for training and evaluating highly qualified athletes. The simulator consisted of the bobsled cockpit, a motion control system, and a graphic monitor. The driver's view of the track was displayed on the monitor. He operated the virtual bob like a real one and all his actions were automatically analyzed by the motion control system which gave the athlete on-line feedback [74]. Similarly, the rowing simulator incorporated a rowing machine, sensors, and a software system, which transmitted signals to a virtual reality system that produced visual, acoustic, and mechanical feedback [75]. Another example of artificial reality was created for teaching and motor learning in gymnastics [76]. The computerized system provided the athletes with annotated animations, two-dimensional graphics, and videos prior to and during face-to-face practical sessions; the system contained a wireless infrastructure that afforded access to all relevant information via an Internet resource.

It can be assumed that training systems utilizing AEs have been developed with the intention of reinforcing training transfer from selected drills to real-world performance. This higher degree of transfer as compared with traditionally used drills can be related to at least three particularities of AE systems:

- A high equivalence of simulated and real performance that is one of the principal conditions for creating AE training systems
- The availability of real-time feedback, which can be utilized to immediately correct performance
- The possibility of creating patterns of optimal performance that are usually achievable only during training in real-world conditions

One more additional advantage of training with AE systems is the possibility of working individually with an athlete to emphasize his/her strengths and correct weaknesses. The disadvantages of these systems are their high cost and the inability to work simultaneously with large groups of athletes.

4 Training Transfer of Motor Abilities

This mode of training transfer is the basis for selecting and implementing any kind of conditioning exercises in the various sports. In fact, compiling a training program in a given sport presupposes the prediction of the anticipated effects of selected exercises on the targeted athletic performance. These expectations are usually based on previous experience, common sense, and available knowledge about training transfer, which are briefly considered below.

4.1 Contralateral Transfer Following One-Limb Strength Training

The contralateral strength training effect is one of the most popular topics among publications devoted to training transfer. This particular interest is mostly concerned with the demands involved in rehabilitating patients with movement restrictions in one limb. However, athletic training needs are also of distinct importance, particularly in sports with asymmetrical movements. The essence of this phenomenon is based on findings indicating that strength training on one side of the body enhances the strength of untrained muscles on the other side of the body. Table 2 summarizes data of 13 studies of contralateral strength transfer following training of one arm or one leg. The selection of studies was based on the following criteria: the participation of relatively young adult subjects, a properly controlled study design that usually included a control group, training duration of not less than 4 weeks, training intensity at maximal or near maximal level, and priority to more recent publications.

The pooled magnitude of the contralateral training effect, as it emerges from Table 2, equals 13.7 %, which exceeds the 7.8 % effect reported in a previously published meta-analysis [90], but is consistent with the strength gain reported by Zhou [91] on the basis of a summary of 40 published studies. This discrepancy between present and earlier data can be attributed to the selection of studies referenced in Table 2; as already mentioned, only data from young healthy volunteers were used in the present review, unlike the previous summaries which analyzed broader age ranges of subjects. The pooled estimate for

Table 2 Summary of studies of bilateral strength transfer following resistance training

Sample, mean ± SD	Training description	Strength mode, gain in contralateral limb, % mean (range of values or ±SD)	Sources
20 male subjects, age 21.8 ± 0.8 years; EXP and C groups	Isometric knee extension; MVC; 4 sessions/week; 12 weeks	Isometric strength; 21.6 (−2.9 to 46.2)	Carolan and Cafarelli [77]
15 female subjects, age 21.9 ± 2.7 years; EXP and C groups	Isometric knee extension; MVC; 3 sessions/week; 8 weeks	Isometric strength; 3.1 (−10.2 to 16.4)	Garfinkel and Cafarelli [78]
20 male and female subjects, age 23–40 years; EXP and C groups	Isometric and isokinetic knee flexion and extension; MVC; 3 sessions/week; 7 weeks	Isometric strength; 13.3 (−3.6 to 30.3)	Kannus et al. [79]
14 male subjects, age 21.3 ± 1.9 years; EXP and C groups	Isokinetic knee extension; MVC; 4 sessions/week; 12 weeks	Isokinetic strength; 20.9 (12 to 29.8)	Hortobagyi et al. [80]
32 female subjects, age 24.8 ± 4.5 years; three EXP and C groups	Isokinetic eccentric contractions; EMS eccentric leg contractions; EMS eccentric arm contractions 4 sessions/week; 6 weeks; total 840 contractions over 6 weeks	Eccentric training effect: MVC isometric 15 ± 20; eccentric MVC 23 ± 30. EMS training effect: MVC isometric 19 ± 20; MVC eccentric 34 ± 35	Hortobagyi et al. [81]
20 male subjects, age 22.2 ± 2.8 years; EXP and C groups	Isokinetic knee extension, 6–8 reps with MVC, 3–6 sets; 3 sessions/week; 12 weeks	Isokinetic MVC in knee extension; 3.9 (−0.3 to 8.0)	Evetovich et al. [82]
15 male subjects, age 26.2 ± 4.6 years; EXP and C groups	Dynamic calf raises and plantarflexion against foot plate with load 70–75 % of 1 RM; 4 sessions/week; 6 weeks	Isometric MVC in plantarflexion: 4.0 (−9.8 to 17.8)	Shima et al. [83]
30 male adult subjects, age 22.6 ± 3 years; two EXP and C groups	Isometric knee extension with voluntary (group A) or EMS (group B); intensity 65 % of MVC, 3 sessions/week; 4 weeks	Isometric MVC; effect of voluntary training 21.4, effect of EMS training 21.1	Zhou et al. [84]
36 male and female subjects, age 21.2 ± 1.8 years; two EXP and C groups	Isokinetic eccentric elbow flexion with fast (group A) or slow (group B) velocity; all reps with maximal effort, 3 sessions/week; 8 weeks	Isokinetic eccentric fast training—gains of MVC: fast eccentric 22.8; fast concentric 23.5; the other regimes—no gains	Farthing and Chilibeck [85]
585 male and female subjects, age 24.3 ± 0.2 years; two EXP and C groups	Dynamic elbow flexion and extension with weights equal to 6–12 RM; 12 weeks	Muscle size gain 1.4 ± 0.3; isometric MVC 5.3 ± 0.7; 1 RM dynamic 10.6 ± 0.8 ($P < 0.05$)	Hubal et al. [86]
115 male and female subjects, age 20.6 ± 6.1 years; four EXP and C groups	Elbow flexion with load ∼80 % of 1 RM; 18 sessions over 6–7 weeks; group A: 1 high speed set, group B: 1 low speed set, group C: 3 high speed sets, group D: 3 low speed sets	1 RM increased by 7 % following program with 3 low speed sets ($P = 0.022$); the other regimes did not produce significant gains	Munn et al. [87]
10 male subjects, age 21.8 ± 0.4 years	Dynamic knee extension and leg press at 80–90 % to MVC, 3 sessions/week; 8 weeks	Isotonic MVC 15.3 ± 3, isometric MVC and fiber composition—no change	Wilkinson et al. [88]
26 male and female subjects, age 24 ± 1.7 years; EXP and C groups	Dynamic plantar flexion MVC 6 reps, 6 sets; 4 sessions/week; 4 weeks	MVC torque increased by 32 ± 30 % ($P < 0.01$); EMG activity increased in both legs	Fimland et al. [89]

EXP experimental group, *C* control group, *1 RM* on repetition maximum, *MVC* maximum voluntary contraction, *EMS* electromyostimulation isometric MVC, 11.6 % (range of values 0–21.6 %), is less than the 16.3 (7–34) % pooled estimate for dynamic MVC, although the difference did not reach statistical significance. This proportion is consistent with findings in other studies that reported training outcomes of both isometric and dynamic contractions [81, 86, 88]. Apparently dynamic contractions are more sensitive to contralateral effects and these higher responses are of distinct importance for athletic practice, where dynamic muscular activities are more prevalent than isometric ones in training programs.

The mechanisms underlying contralateral strength transfer are still under debate although several extensive reviews introduce plausible explanations of this widely considered phenomenon [90–94]. Among the physiological mechanisms proposed, several seem persuasive and are reviewed below.

4.1.1 Neural Interactions Between Cerebral Hemispheres

The central drive from the cerebral hemisphere, where motor commands to trained muscles are generated, diffuses to the symmetrical (same-side) hemisphere in which neural signals to homologous muscles of the untrained limb descend [92]. This supposition is laid out in the "bilateral access" hypothesis, which proposes that the contralateral hemisphere receives neural input from the dominant hemisphere via the corpus callosum. Subsequently, neural adaptation in the untrained limb occurs during motor task execution with the opposite limb [92]. Another "cross-activation" hypothesis presupposes that execution of a unilateral motor task causes cortical activation in both hemispheres. Corresponding neural adaptations elicit task-specific changes and increase corticospinal excitation in homologous muscles of the untrained limb [95]. The enhanced force output can be associated with improved synergist coordination and inhibition of antagonist activity [93].

4.1.2 Spinal Cord Mechanisms

One more explanation of contralateral strength transfer pertains to spinal cord mechanisms. It is known that spinal circuits affect motor output via reflex actions on motoneurons and/or by modulating supraspinal commands. The hypothetical motor effect in the untrained limb occurs with cross-hemicord connections, which activate muscle spindles in the homologous muscles [94]. This supposition is supported by the outcomes of electromyostimulation (EMS) training, which induces contralateral transfer similar to voluntary training [81].

4.1.3 Peripheral Blood Flow Activation

Another factor that is thought to affect contralateral training transfer is the increase of peripheral blood flow in the untrained limb [96]. It has been suggested that such nonmuscular adaptations can contribute to the contralateral motor effect and prevent central fatigue which reduces the ability of the CNS to drive the motoneurons optimally [93]. It is suggested that such a factor may assist in obtaining a greater training effect after highly intensive unilateral exercises. The value of this effect regarding the untrained limb may be relatively small but still important.

4.1.4 Hormonal Impact on Muscle Hypertrophy

A further potential contributor to the motor effect is associated with a possible hormonal impact and the muscle hypertrophy induced by training the unilateral limb. Unilateral training may induce a significant elevation of endogenous hypertrophy-promoting hormones and subsequently elicit changes in muscular strength and muscle size in both the trained and untrained limbs. Indeed, such changes in the muscle size of untrained limbs were found in male and female subjects following 12 weeks of unilateral training; these gains were coupled with a remarkable increase in strength [86]. These findings are not consistent with the data of a later study, where unilateral training responses were controlled using more precise methods such as muscle biopsy, computerized muscle tomography, analysis of endogenous anabolic hormones, and the monitoring of muscle strength [88]. Eight weeks of training of young male volunteers did not cause any changes in systemic hormones concentration although it did induce local hypertrophy, shifts in fiber types, and a significant increase in muscle strength of the trained leg. No changes were noted in cross-sectional area (CSA), so that fiber composition and muscle strength in the untrained leg appear to be the only valid control [88]. This assumption of a lack of hypertrophy in the untrained limbs is also supported in extensive reviews of cross-transfer after unilateral training [91, 93, 94].

4.1.5 Summary

Concluding this section it is worth noting that in any case, strength gain in untrained limbs is much less than in trained limbs, reaching about 60 % [91] or 50 % [94] of the values obtained in the limbs subjected to unilateral training. Nevertheless, this relatively small effect usually reached a level of significance and is widely used in clinical and rehabilitation practice. This apparent transfer of strength training results is attributed mostly to the neural mechanisms of muscular adaptation where cortical, subcortical, and spinal levels of regulation share responsibility. From the viewpoint of the present review, the extent of strength transfer from unilateral training to the contralateral limbs in athletes' preparation is of special interest. Unfortunately, much of the research and its findings have been obtained in studies with non-athletic volunteers (see Table 2). Taking into account the high contribution of morphological adaptations in athletic training to the enhancement of strength capability, the extent of training transfer to untrained limbs should logically be less. On the other hand the hormonal shift induced by athletes' training with other limbs can be much stronger than among non-athletic trainees and hypertrophy in untrained limbs cannot be ruled out. This assumption is supported by data from Hubal et al. [86], who reported a small but significant increase of size in untrained muscles in a study of 585 young volunteers. Furthermore, such factors as increased peripheral blood flow in untrained limbs may make a larger contribution in muscular adaptation when the workload level is sufficiently high, as is characteristic of athletes' training. Apparently the contralateral effects under consideration can reasonably be exploited in training low-level and injured athletes and for diversification of the program for trained, elite, and sub-elite athletes.

4.2 Arm–Leg Cross-Transfer in Endurance Training

It is commonly accepted that physical training enhances the work capacity of trained muscles, producing the so-called specific effect. It is also known that such training also increases the performance capacity of untrained muscles eliciting a transfer effect [97], which is of particular interest in this review. A number of research projects have been devoted to examining the transfer of endurance in training performed separately with either arms or legs involving subjects of various ages, athletic levels, and workloads. These studies were related to rehabilitation after various neuromuscular deceases but they also entail possible methodological insights for designing training regimes.

Figure 1 summarizes the findings of various studies of 5–12 weeks in duration, in which subjects trained using arm exercises (arm cranking, wheelchair) or leg exercises (leg cycling, treadmill running) [97–103]. Performance gains were evaluated in both arms and legs using incremental stepwise tests until exhaustion to determine peak power and maximum oxygen consumption. The data below display the details of training responses assessed by gains in maximum oxygen consumption:

1. Training with either arms or legs produces a transferred cross effect on the untrained limbs—on average 32 % of the gain recorded in the trained limbs (i.e., specific effect) with a wide range of variation from 5.7 to 93 %; these large variations reflect the high variability of training groups in the different studies, which included young athletic subjects or middle-aged and elderly persons.

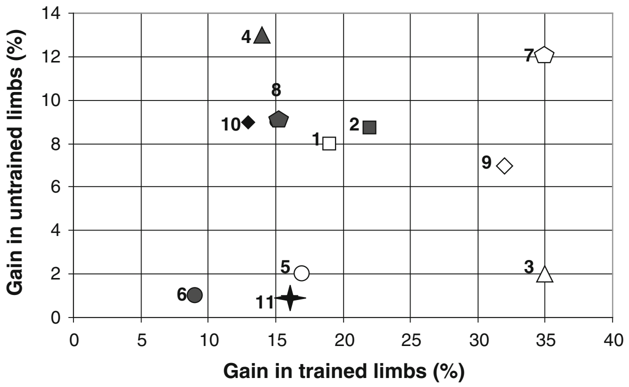

Fig. 1 Gain in oxygen consumption following training lasting 5–12 weeks separately for legs or arms measured by testing the trained and untrained limbs. *Open symbols* signify data for arm testing; *filled symbols* signify data for leg testing. *1–2* Pogliaghi et al. [98], *3–4* Tordi et al. [101], *5–6* Bhambani et al. [99], *7–8* Lewis et al. [97], *9* Loftin et al. [100], *10* Roesler et al. [102], *11* Magel et al. [103]

2. The specific effect producing by arm training is usually much more pronounced as compared with leg training; this can reflect a substantially lower initial training status of arm—compared to leg—muscles. This is especially characteristic of relatively low trained subjects [98].
3. The extent of the transfer effect produced by leg training (filled symbols in Fig. 1) is much higher than for arm training (open symbols); this discrepancy can be explained by the larger muscle mass involved in leg exercises and the correspondingly higher impact on cardiorespiratory system adaptations [104].

The widely documented arm–leg endurance transfer is generally attributed to the central mechanisms of training adaptation and especially to an increase in cardiorespiratory capacity [98, 101, 105]. Local adaptations occurring in trained muscles largely contribute to the specific training effect but the transfer of working capacity to untrained limbs is restricted. Examination of changes within muscle fibers induced by 8 weeks of bicycle endurance training revealed increased volume density of mitochondria and enhanced capillarization in trained leg muscles [102]. However, capillary per fiber ratio in arm muscles remained unchanged, whereas mitochondrial volume density in arm samples decreased considerably. Despite these unfavorable peripheral changes the subjects increased their maximum oxygen uptake in arm testing by 9 % which can definitely be attributed to the central mechanism of adaptation [102]. These data are consistent with findings of Bhambani et al. [99], which emphasized the role of peripheral adaptations in obtaining relatively high aerobic power following arm or leg training, whereas the transferred training effect to the untrained limbs was relatively small (Fig. 1).

It should be noted that studies of arm–leg transferability were conducted mostly with non-athletic and untrained volunteers. Data from the rare studies that employed athletic subjects indicate that the role of training specificity is reinforced with increased athletic preparedness. Indeed, 10 weeks of endurance arm training of young athletic subjects caused considerable gain in work capacity and maximum oxygen uptake in arm ergometry and minimal changes in treadmill running [103]. Similarly, 4 weeks of highly intensive training on the bicycle ergometer by young volunteers did not produce any remarkable changes in work output and metabolic estimates obtained on the kayak ergometer [106].

Summarizing these data, the existence and role of arm–leg cross transfer of endurance trainedness can be firmly postulated. This phenomenon has distinct importance for both the rehabilitation of clinical patients and for athletes. In the latter case, positive training transfer is strongly determined by the relationship between central and peripheral adaptations occurring during the training of either the legs or arms. With increased athletic preparedness, the role of peripheral sport-specific adaptations increases as well [107, 108]. Therefore, the contribution of a more generalized central mechanism of adaptation decreases; correspondingly, the chances of cross-limb transferability of physical fitness decrease as well.

4.3 Transfer of Strength Training in Endurance Performance

Strength exercises have long been an obligatory part of athletes' preparation in various endurance sports. Their implementation was initially preceded by the successful experiences of prominent coaches, anecdotal reports, and common sense. Subsequently, many publications presented arguments supporting this concept (Table 3). However, some studies found no positive impact of strength exercises on endurance performance (Table 4).

On the basis of extensive research findings, various methodological guidelines advocate the concurrent administration of event-specific endurance workloads and strength exercises such as high resistance, heavy weights, and explosive type exercises [109–114]. The approach to strength training is based on suppositions related to morphological, physiological, and biomechanical adaptations. It was widely assumed that appropriate fitness programs induce the strengthening of sport-specific muscle groups, tendons, and ligaments, stimulate event-specific musculoskeletal hypertrophy and muscular topography [15, 20, 107]. It is commonly believed that athletes can positively transfer increased strength abilities to their technical skills, augmenting force and power in phases of dynamic interaction with the sport-specific environment. The underlying mechanisms that affect such positive transfer remain unclear although several recently proposed theories seem persuasive.

4.3.1 Hypertrophy and Transformation of Muscle Fibers

Muscle hypertrophy and transformation of muscle fibers have been considered plausible mechanisms of strength training transfer in endurance performance. Unlike endurance training, only concurrent training elicits the profound muscle hypertrophy directed primarily to fast-twitch (FT) fibers. Findings by Kraemer et al. [123] indicate that concurrent strength and endurance training produces pronounced hypertrophy of fast oxidative twitches (FTa) as well as a significant shift (in percentages) from fast glycolytic fibers (FTb) to FTa type. These findings are not completely consistent with those of Nelson et al. [124] and Hakkinen et al. [125], who reported that concurrent strength and endurance training causes significant increases in slow-twitch (ST), FTa, and FTb fiber areas. An earlier study by Sale et al. [126] also found a shift in muscle fibers to a more oxidative type with a higher percentage of ST fibers and greater aerobic enzyme activity. These data were supported by later findings [127] indicating more selective outcomes of concurrent endurance and strength training, which resulted in a significant increase of ST fibers and a considerable shift of muscle fibers to a more oxidative pattern supported by increased aerobic enzyme activity in the mitochondria. Summarizing these data one can conclude that implementing a strength program as part of endurance training produces a profound hypertrophic process involving FTa, ST, and some FTb fibers and, in this way, may shift fiber composition to a more aerobic pattern. In addition, an increased CSA in the muscles serves as a prerequisite for more efficient force and power application in event-specific technical skills.

4.3.2 Increasing Work Economy

It has been proposed that strength training, and in particular plyometric and explosive-type exercises, increases the stiffness of tendons and other elastic components of muscles, which can approach the stiffness level of tendons [128, 129]. This increased stiffness allows better storage and utilization of the energy absorbed during the eccentric phase of muscular contraction and in this way improves work economy. This mechanism of greater training-induced work economy is of particular importance for athletic skills like running and jumping, where amortization phases allow the storage and subsequent recoil of elastic energy of stretched muscles. Indeed, significant enhancement of work economy has repeatedly been found following concurrent strength and endurance training in

Table 3 Summary of studies which found positive transfer of strength training to endurance performance

Sample, mean ± SD	Training description	Study outcomes	Sources
12 female distance runners; age 30.3 ± 1.4 years; EXP and C groups	Endurance running 20–30 miles/week 4–5 days/week in both groups; EXP group added weight training (14 drills) 3 days/week for 10 weeks; C group performed running only	No difference in VO_{2max} and body composition in either group; significant gain in running economy and strength variables in EXP group	Johnston et al. [109]
15 female cross-country skiers; age 17.9 ± 0.3 years; EXP and C groups	Endurance training about 60 % total work in both groups; focus on maximum strength in EXP group vs. general strength program for C group; 9 weeks, 5 days/week	Significant superiority of EXP group in ski ergometer performance improved by higher work economy, and in strength tests	Hoff et al. [110]
15 male triathletes; age 22.7 ± 3.8 years; EXP and C groups	Endurance aerobic training lasted about 20.5 h/week in both groups; EXP group added heavy weight training for lower limbs (3–5 RM) 2 days/week; 14 weeks	EXP group but not C group significantly improved running performance, running economy, and maximum strength estimates	Millet et al. [111]
17 male distance runners; age 25 ± 4 years; EXP and C groups	Aerobic endurance training in both group with volume 60–80 km/week; EXP group added plyometric training 2–3 days/week; 6 weeks	EXP but not C group significantly improved 3-km running performance, running economy, and jumping performances	Spurs et al. [112]
49 male sport students; age 21.4 ± 1.3 years; four EXP and one C groups	Endurance running program (E), strength circuit training (S), E + S combined in one session, S + E combined in one session; 12 weeks, 2 days/week	Significant superiority of E + S group over other groups in 4-km running, VO_{2max}, and in running to exhaustion test	Chtara et al. [113]
19 male cross-country skiers; age 23.1 ± 3.7 years; EXP and C groups	Total training volume about 10.6 h/week in both groups, 11 sessions/week; program of EXP contained explosive strength exercises; 8 weeks	EXP group but not C group significantly improved work economy, force generation, and integrated EMG indices	Mikkola et al. [114]
43 trained male rowers; age 25.1 ± 3.8 years; three EXP and one C groups	Rowing endurance training about 460 min/week in each group; additional strength program 2 days/week: (1) 4 drills to failure; (2) 4 drills not to failure; (3) 2 drills not to failure; (4) no strength training—control: 8 weeks	Programs with 4 and 2 reps not to failure led to significant gains in brief and longer rowing tests; programs with 4 reps not to failure causes the best progression in maximum strength variables	Izquierdo-Gabarren et al. [115]

VO_{2max} maximum oxygen uptake, *EXP* experimental group, *C* control group, *EMG* electromyography, *RM* repeated maximum

distance runners [109, 112], cross-country skiers [110, 114], and triathletes [111]. Apparently this mechanism of enhanced work economy is closely connected with increased stiffness of the musculotendinous system.

4.3.3 Enhancement of Peripheral Blood Circulation

Force application at a level of more than 15 % of maximum effort causes vasocompression that restricts peripheral blood flow; efforts reaching 70 % and more of maximum produce occlusion of the capillary network and block local blood flow [130]. Consequently, the heart must pump blood against greater peripheral resistance and the muscles suffer from local ischemia [131]. Increasing the maximum force of the appropriate muscles enlarges their strength reserves; muscular efforts can be performed at a more comfortable level with more favorable conditions for local blood circulation. Thus, the suppressive impact of vasocompression can be reduced or entirely eliminated [110]. It is worth noting that this positive effect can be obtained when maximum force is increased under proper task-specific conditions but not in general fitness exams.

4.3.4 Increasing the Total Amount of Training Stimuli

According to the overload principle, training adaptation occurs when the magnitude of training workload surpasses the individuals' habitual level [16]. Implementation of strength training in a habitual program of endurance routines enlarges the input of training stimulation and elicits profound metabolic and endocrine responses, which can approach the upper border of human adaptation. Following the classic theory of stress [132] and its interpretation for sport science [107], when available biological resourses are sufficient for metabolic, neuromuscular, and hormonal adjustment, athletes attain higher levels of training adaptation and enhance their working capacity. If training demands surpass the limits of athletes' adaptability, they accumulate residual fatigue and may become overtrained [133, 134]. The rare studies of "dose–response" relationships indicate that optimal but not maximal training demands determine a more favorable transfer of strength training in athletic performance [115, 135]. It can be suggested that optimally dosed strength workloads can contribute to athletes' preparedness thanks to an increased amount of training stimuli.

Table 4 Summary of several studies which did not find positive transfer of strength training to endurance performances

Sample, mean ± SD	Training description	Study outcomes	Sources
18 varsity male rowers; two EXP and C groups	Isokinetic strength training with high velocity or low velocity or no strength training (C) combined with rowing drills; 5 weeks, 4 days/week	Significant gains in EXP groups in peak leg torque; no differences between groups in 90 s rowing ergometer test	Bell et al. [116]
37 trained young swimmers, age 11–12 years; EXP and C groups	Conventional swimming training combined with strength sessions 2 days/week: in-water strength drills (C) vs. dry-land drills (EXP); 25 weeks	Superiority of dry-land group in strength tests and significantly higher gains of in-water group in swimming performances	Bulgakova et al. [117]
22 intercollegiate swimmers, age 19.3 ± 0.22 years; EXP and C groups	Swim training 4–6,000 miles/day each day; resistance program 8–12 RM 3 days/week (EXP) or swim only (C); 12 weeks	No difference in power on swim bench and in water; no benefits of EXP group in sprint and stroke efficiency	Tanaka et al. [118]
30 elite male and female rowers; EXP and C groups	Traditional weight training (EXP) vs. rowing ergometer work (C) combined with endurance program; 14 weeks, 4 day/week	No difference between groups in squat and bench pull; superiority of no-lift (C) group in the 2,000-m rowing test	Murray et al. [119]
18 varsity male rowers; two EXP and C groups	Traditional weight training; (1) high-load low reps, (2) low-load high reps combined with rowing; (3) C—no-lift rowing group; 8 weeks, 2 days/week	All groups enhanced their 2,000-m rowing performance; no difference between groups	Gallagher et al. [120]
22 recreational runners; age 40 ± 11.7 years; two groups	Endurance program combined with strength (leg and trunk exercises) vs. pure endurance program; 8 weeks, 4 days/week	No difference between groups in maximum oxygen uptake, running marathon performance and economy, stride length and frequency	Ferrauti et al. [121]
26 male qualified junior swimmers; age 14.1 ± 0.4 years; two groups	Endurance program combined with dry-land power training vs. pure swimming endurance program; 6 weeks, 2 sessions/day	No significant benefits of EXP group in sprint trials although it obtained significant superiority in water power test	Sadowski et al. [122]

EXP experimental group, *C* control group

4.3.5 Additional Factors Impeding Strength Transfer

It is noteworthy that the above mechanisms affecting the positive transfer of strength training cannot be utilized equally in different sports. Factors such as the sport-specific environment strongly determine the possibility of exploiting these mechanisms to attain beneficial athletic performance. Frequently major studies that do not find a positive transfer of increased strength abilities deal with aquatic locomotion (Table 4). Indeed, as compared with land-based locomotion, aquatic sports contribute little to the eccentric phases of movement patterns and this restricts the utilization of increased musculotendinous stiffness for enhancing work economy. Relatively long-term phases of oar air transfer in rowing and hydrostatic force compensation for gravitation in swimming produce better conditions for muscular relaxation and, correspondingly, beneficial peripheral blood circulation. The particularities of water stroke mechanics strongly determine the neuromuscular patterns of athletes' propulsive movements and this largely restricts the transfer of strength abilities, which increase in land-based conditions. Even when dry-land exercises have been designed to simulate as closely as possible the movement patterns of swimmers [117, 118] or rowers [116, 119], their execution did not produce any appropriate transfer to sport-specific performance. It has been suggested that strength training transfer requires a delay for transformation and stronger athletes might utilize their fitness benefits after a period of latency [120]. However, this hypothesis was not supported by the outcomes of season-long studies of swimmers [118], which showed similar performance improvement after tapering in athletes who used free-weight strength training and athletes who practiced a swimming-only program.

One more mechanism impeding transfer of strength training in endurance performance may be associated with the residual fatigue caused by increased workloads, which restricts the acute and cumulative effects of strength sessions. Muscle fiber hypertrophy presupposes the availability of energy resources for protein synthesis [107]. Executing 8–10 endurance sessions a week, which is typical for endurance sports, offers little opportunity to implement this recovery process. One more remark about the amount of training stimuli is in order. It is possible that supplementary strength programs may produce excessive training stimulation and that athletes may be unable to adjust to the increased demands.

4.3.6 Summary

It should be noted that the extensive findings demonstrating the synergistic effect of strength and endurance training provide serious substantiation and legitimization for their concurrent administration, but a smaller number of studies, which did not find any positive transfer of strength training, cannot be ignored. One possible resolution for these contradictory findings may be found in block periodization [17, 136–138], which proposes the separation of generalized and event-specific training workloads in appropriate blocks–mesocycles. The principal benefits of such separation lie in the avoidance of conflicting physiological responses while providing sufficient training stimulation [23, 107]. Additional benefits can be obtained by combining extensive aerobic with anabolic strength exercises, and highly intensive anaerobic with explosive-type and plyometric exercises [17, 138].

4.4 Impact of Endurance Workloads on Strength/Power Performances

World-wide, training strength/power athletes involves the inclusion of endurance workloads for improving general cardiorespiratory fitness, reducing body fat, and reinforcing aerobic recovery during the performance of multiple sets of highly intensive strength/power exercises. Several studies have shown that execution of an endurance program does not interfere with strength development [126, 139, 140]. These studies were conducted with sedentary or untrained volunteers using a relatively low overall volume of training. A larger group of publications whose research findings were usually obtained from studies of well-trained athletes showed an interference effect and reported that endurance workloads compromise the development of strength/power ability [123, 141–145]. In light of these inconsistent data, a number of physiological factors should be taken into account, which may determine whether endurance workouts have a negative training transfer effect on the strength/power potential of athletes.

4.4.1 Hypertrophy and Transformation of Muscle Fibers

As has been claimed repeatedly, neuromuscular system demands for execution are different for a combined strength and endurance program and for strength/power training alone. Each requires different patterns of neuromotor activation [125, 141]. Directed strength/power training induces muscle hypertrophy of slow-twitch and fast-twitch FTa- and FTb-type fibers [123, 125, 142]; however, the extent of FT hypertrophy is more profound than in ST [124, 143]. It should be noted that several studies found no differences in muscle hypertrophy induced by concurrent strength and endurance training as compared with strength training only [125, 126]. Nevertheless, many studies have reported an interference effect in concurrent strength and endurance training, which compromises neuromuscular adaptation to forceful efforts and affects fast-to-slow fiber transition that attenuates FT-type hypertrophy [125, 144, 145]. It has also been shown that a concurrent program does not induce an increase in the size of the muscle fibers, which may explain the lower strength gain produced by this type of concurrent training [123, 125]. Summarizing the findings of several studies Elliott et al. [146] claimed that long-term administration of endurance workloads during the preparation of power athletes decreases the percentage of CSAs of fast-twitch fibers that compromises the development of strength and power abilities. Furthermore, the changes of myosin isozymes from fast to slow isoforms induced by endurance workloads suppress the manifestation of maximal strength/power abilities [147, 148]. Therefore, the commonly held position today is that concurrent strength and endurance training disrupts the hypertrophy pattern produced by strength/power training alone and elicits fiber transformations that are favorable for endurance but detrimental to strength/power development.

4.4.2 Specificity of Neural Adaptations to Strength and Endurance Training

Neural adaptations induced by strength/power training are characterized by a profound specificity that affects the recruitment of an appropriate number of motor units, changes in the firing rate of motor units (rate coding), and synchronization of various motor unit activities [149]. The recruitment of motor units, which regulates the level of muscular effort, adapts specifically to prolonged sustained efforts and this adaptation decreases the ability to rapidly generate force and power [150]. It is known that the discharge rate of motoneurons is training-specific and increases to maximal level as the result of adaptations to force/power contractions [151]. Similarly, the magnitude of synchronized discharge among various motor units strongly depends on the mode and character of the predominant training [152].

One more factor affecting maximum force/power is the coordination of antagonist muscular activity. Hakkinen et al. [125] found a reduction in the co-activation of antagonist muscles following concurrent strength and endurance training in contrast to a strength-trained group, which avoided this coordination impairment and enhanced explosive strength markedly. Furthermore, large groups of explosive exercises exploit neural mechanisms governing stretch-shortening muscular activity. Directed explosive strength training increases the myotatic reflex of stretched muscles and suppresses inhibitory signals from the Golgi tendon organs [149]. Neuromuscular fatigue decreases stretch-reflex sensitivity and markedly reduces the power benefits of stretch-shortening action [153]. Apparently, the effectiveness of stretch-shortening exercises declines sufficiently when they are administered concurrently with energy-demanding endurance workloads. Moreover, residual fatigue induced by the endurance component of a training program may attenuate physiological responses to power exercises and increase the likelihood of injuries [146].

4.4.3 Hormonal Factors Affecting Strength and Concurrent Training

Hormonal responses, which are closely connected with the intensity, duration, and character of exercises, specifically reflect physiological adaptations in athletes. According to Viru [107] androgen levels largely subordinate the synthesis of myofibrillar proteins whereas thyroid hormones play a distinct role in the synthesis of mitochondrial proteins. Testosterone, cortisol, and the ratio between them are commonly used as indicators of anabolism [154, 155] and are widely used for evaluating the effectiveness of strength/power—but not endurance—training. The studies by Kraemer et al. [123] and Bell et al. [156, 157] have demonstrated that a highly intensive strength/power program produces increased testosterone and decreased cortisol response, whereas concurrent strength/endurance training causes increased exercise-induced cortisol secretion. Therefore, strength/power training elicits a profound anabolic response, which changes radically towards a catabolic response when strength/power exercises are combined with endurance workloads. Apparently the hormonal response induced by the endurance component of a concurrent training program substantially modifies the endocrine adaptation of strength/power athletes; this hormonal shift may suppress and decrease the training transfer of strength/power exercises to athletic performance.

4.4.4 Intracellular Regulation Induced by Strength and Endurance Exercises

One more source for the detrimental impact of endurance workloads on the development of strength/power abilities can be found in molecular biology: evidence has emerged related to the signaling mechanisms that determine physiological adaptations to different forms of physical exercises. It has been suggested that adaptations to resistance and endurance training are mediated by interactions between signaling pathways [158]. More specifically, high resistance strength exercises activate a growth-associated network, which modulates muscle-protein synthesis and produces muscle hypertrophy [159]. On the other hand endurance exercises activate signaling mechanisms of metabolic adaptations associated with changes in energy phosphate levels intended to maintain energy homeostasis [160, 161]. Concurrent activation of both signaling networks leads to the inhibition of protein synthesis and attenuation of the strength training effect [162]. Moreover, it has been found that endurance workouts acutely decrease the rate of protein synthesis and this suppression lasts for several hours [163, 164]. Therefore, molecular biology studies indicate antagonistic relationships between anabolic signaling mechanisms and the energy-modulating signaling that regulates adaptation to endurance training. The consequence of such antagonism is a negative impact of endurance training on hypertrophy response and strength-training adaptation.

4.4.5 Summary

Apparently, endurance workloads can produce a negative impact on the performance of strength/power athletes; thus, administration of these workloads in their preparation should be reasonably restricted. However, some sports, such as combat disciplines and ball games, demand extreme manifestations of explosiveness over prolonged time periods, exerting both strength/power and endurance abilities. From this viewpoint consecutive but not concurrent developing of power and endurance components can provide a real solution to this problem [138].

4.5 Cross-Training

Cross-training as it pertains to training designs involves different sports or training forms intended to (1) improve general and/or event-specific fitness for a given sport; (2) diversify and enrich the training routine of recreational athletes; (3) provide correct preparation for athletes in multi-sports activities such as triathlon, duathlon, or modern pentathlon.

The first aim directly relates to previously considered situations that incorporate power/strength exercises in preparation for endurance athletes (Sect. 4.3) or endurance workloads in the training routine of power/strength athletes (Sect. 4.4). The history of various sports offers many examples, such as rowers and kayakers practicing skiing, bicyclists using skating, skiers using cross-country running because of typical seasonal restrictions on specific outdoor sports. These experiences remain relevant and still have practical importance although contemporary elite sport gives abundant opportunities for broader utilization of event-specific drills. In addition, the summary of findings from well-controlled studies indicates that physiological gains, such as maximum oxygen uptake (VO_{2max}) and lactate threshold, are in any case much higher following specific exercising than after non-specific training forms [165]. Nevertheless, alternative exercises, such as swimming for runners or skiing for swimmers, can be reasonably used for active recovery, general conditioning, and injured athletes who are limited in terms of performing their main exercise [165].

The second aim of the application of cross-training pertains to the training exercise settings of recreational athletes. Indeed, combining several modes of physical activity instead of only one promises some benefits for untrained and moderately trained individuals. These benefits can be successfully achieved when workloads correspond to the overload principle, cross-training activities involve large muscle mass, the workloads administered are mostly moderate and not of high intensity, and the whole program is directed at increasing general but not sport-specific fitness [166]. Additional benefits of such programs include relief from boredom, prevention of injuries, and recovery from sport-specific injuries. The effectiveness of this cross-training approach is supported by findings of studies conducted with recreational athletes [167, 168].

The third aim refers to cross-training effects in athletes practicing multi-sport activities. Triathlon, as an Olympic discipline, has become a popular sport around the world, where cross-correlations have been found between workloads and results in swimming, cycling, and running. The outcomes of long-term studies with elite athletes have demonstrated that cross-training effects occur between cycling and running, whereas swimming performance is not affected by workloads in land-based sports [169]. The exclusive status of swimming in terms of cross-training effects can reasonably be explained by the salient specificity of this discipline in terms of peripheral and neuromuscular adaptations. This is quite different from the interrelations between cycling and running workloads. It has been shown that training transfer from running to cycling is higher than vice versa [165, 169]. The reasons for the superiority of the running cross-training effect pertain to higher maximum heart rate than in cycling, higher mechanical efficiency, and more effective storage-recoil of elastic energy, higher pulmonary ventilation, and beneficial peripheral blood flow, whose efficiency is greater when the body maintains an erect position, muscle pumping is coordinated with stride frequency, and stretch-shortening cycle activity increases blood flow [170]. It can reasonably be claimed that cross-transfer effects occur to a higher extent for moderately fit athletes and much less in the preparation of elite athletes [169].

5 Conclusions

Properly differentiated training transfer with regard to the enhancement of movement skills and developing motor abilities strongly depends on the athletes' skill qualifications; for low- and medium-level athletes the transfer effect is higher than for highly trained counterparts. The evidence of bilateral motor skill transfer indicates its distinct value for acquiring and perfecting asymmetrical movement techniques such as dribbling, ball shooting, etc. Biotechnological interventions like mental imagery, biofeedback training, and AEs help to facilitate training transfer from lab and field settings to the technical preparation of athletes. The transfer of trained motor abilities has been considered with reference to one-limb training, arm–leg cross-effects, and workload interaction, when endurance athletes utilize strength/power exercises and strength/power athletes practice endurance training routines. The widely accepted empirical paradigm of the positive impact of strength training on endurance performances is supported by many studies, but disclaimed by others. The physiological mechanisms underlying the benefits of strength training are associated with hypertrophy and the transformation of motor fibers, increased work economy and peripheral blood circulation, and elevation of the total amount of training stimuli. The disadvantages of combined strength/endurance training have been mentioned with regard to the specificity of the aquatic environment, the deficit of energy resources for protein synthesis, and the accumulation of residual fatigue that increases overtraining risks. Consideration of the impact of endurance workloads on strength/power performances is less contradictory; the commonly held position by researchers maintains that endurance workloads interfere with strength/power preparedness causing negative morphological, neural, hormonal, and intracellular responses. Despite that, the combined development of strength/power and endurance capabilities remains important in several disciplines like combat sports and ball games, where the specific fitness profile demands readiness for repeated explosive efforts during a prolonged fight or match.

Cross-training as a form that combines exercising in various athletic disciplines has distinct benefits for general fitness programs and for the preparation of recreational athletes, but it offers no advantages in the preparation of qualified athletes in certain sports; it is also known that the transfer effect from an alternative discipline is in any case less than the specific effect of training in a targeted competitive sport. At the same time cross-training effects are of paramount importance for athletes practicing multi-sport activities like triathlon, duathlon, modern pentathlon, etc.

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