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Effects of heavy resistance training on strength and power in upper extremities in wheelchair athletes

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Abstract

Little is known about strength training in subjects with spinal cord injury (SCI), especially in athletes performing competitive sports.

Sixteen male subjects participated in this study - eight with SCI and eight healthy physical education students (control subjects). The eight-week program consisted of heavy-resistance exercise performed twice per week with ten to twelve repetitions in five sets. Subjects' performances were tested in static and in dynamic condition concerning several strength and power parameters. Furthermore, we tested 10m-sprinting performance in wheelchair athletes.

Overall, wheelchair athletes as well as control subjects achieved similar results: In almost all parameters both groups improved considerably in post-testing. Regarding percentages in most strength and power parameters wheelchair athletes showed even a tendency to higher profit from the strength training performed in the present study. But using analyses of group differences only the comparison of effects on rate of force development (p=0.010) resulted in a significant higher improvement for wheelchair athletes.

In contrast to hitherto assumptions about minor adaptation capacities to training exercises in SCI-patients our study proved clear effects of strength training. In conclusion, we suggest that heavy resistance training should be of increasingly importance in wheelchair sports.

Keywords: heavy resistance training, strength, power, wheelchair athletes, paraplegia, Tetraplegia

Introduction

In most sports general and specific strength training is a critical component to success in competition. Recommendations for exercises and training stimuli are based on experiences of coaches and particularly on comprehensive research in sports science. For more than 40 years numerous studies have dealt with effects of resistance training and its physiological basis. Therefore, training strategies and designs are optimized for athletes in sports depending on strength and power properties. Referring to Knuttgen and Komi strength is the "*ability to exert maximal force*" (21, p. 5) and referring to Schmidtbleicher power is the "*ability of the neuromuscular system to produce the greatest possible impulse in a given time period*" (21, p. 381).

Although, wheelchair sports are of growing popularity as recreational and competitive sports there is a lack of knowledge regarding precise guidelines for specific training designs, especially in strength training. But it is obvious that most wheelchair sports depend on strength and power of upper extremities and these abilities should be developed preferred by heavy resistance training. It is not yet clear if training regimes of high performance athletes could be transferred to training in wheelchair sports.

Studies in sports medicine and biomechanics dealing with spinal cord injury (SCI) patients and athletes have focused on analyzing endurance training, metabolic and cardiorespiratory fitness, whereas in most experiments forearm ergometer exercise were used (2, 13, 30). More than 20 years ago parameters of endurance capacity were already measured in SCI subjects (12). Several studies found impaired performance in these subjects due to "unique changes in metabolic, cardiorespiratory, neuromuscular and thermoregulatory systems, which reduce their overall physiological capacity" (2, p. 26). Athletes with spinal cord injury show a reduced physical capacity by the "direct loss of motor control and sympathetic influence below the level of lesion" (13, p. 642) leading to relatively low values of oxygen uptake and power output. These impairments are caused by reduced maximal heart rate (spinal lesion above TH1), lower stroke volume, venous pooling in the lower limbs because of reduced muscle pump action, less preloading of the heart ventricles, slower increase of oxygen consumption during steady-state exercise, and impaired thermoregulation (2, 26). But strong variations in aerobic and anaerobic work capacity were found in wheelchair athletes depending on functional classification and training status (2, 31, 32). As a result, one can speculate about minor adaptation capacities to training exercises in general in SCI-patients with tetraplegia or paraplegia. Tetraplegia refers to “impairment or loss of motor and/ or sensory function in the cervical segments of spinal cord due to damage of neural elements within the spinal canal. Tetraplegia results in impairment of function in the arms as well as in the trunk, legs and pelvic organs“. Paraplegia refers to the “impairment or loss of motor and/ or sensory function in the thoracic, lumbar or sacral (but not cervical) segments of the spinal cord, secondary to damage of neural elements within the spinal canal. With paraplegia, arm functioning is spared, but depending on the level of injury, the trunk, legs and pelvic organs may be involved” (23, p. 266).

Regarding strength and power in wheelchair athletes there is currently limited research. Few papers have addressed guidelines for training in SCI subjects but on one hand experimental evidence is unclear (30) on the other hand recommendations are *not* referred to heavy resistance training in SCI athletes aiming at improved performance in competition (8). Therefore, specific training adaptations have yet to be documented in these subjects. Commonly, in SCI patients training is performed during process of rehabilitation including exercises on wheelchair ergometer, kayak ergometer, hand cycling, arm cranking, and with circuit training regimes. In all available experiments merely moderate intensities were used (3, 5, 8, 9, 15, 17, 18, 24, 30). Moreover, there is a lack of studies dealing with SCI subjects using biomechanical analysis to measure several specific parameters comparable to evaluation in high performance athletes (29). And few experiments available in the literature used merely isokinetic measuring devices featuring less relevance for most sports (1, 3, 8, 19, 20, 27, 28).

Methods

Experimental approach: Objective of this study was to compare the effects of resistance-training on strength and power in upper extremities in wheelchair subjects and in control subjects (physical education students). To address the primary hypothesis of this investigation that SCI athletes profit from strength training all subjects were assigned to eight-week resistance training. Exercises were performed twice per week with program variables of 70 to 85% intensity of one repetition maximum and 5 sets not exceeding 12 repetitions. Following variables were assigned as dependent variables: in bench throw we measured maximal velocity (v_{max}), maximal acceleration (a_{max}), and time intervals representing the initial acceleration (t1 and t2) of the barbell. In static condition we recorded maximal strength (F_{max}) and maximal rate of force development (MRFD). Second, we evaluated in dynamic bench press *one repetition maximum* (1RM) and *strength endurance* (SE). Furthermore, we evaluated 10m-sprinting performance in wheelchair athletes. This parameter enabled us to examine the potential transfer of strength training to concrete demands in competition. Assessments were performed before and after the training period.

Subjects: A total of sixteen male subjects volunteered to participate in the present study - eight with SCI and eight healthy physical education students conversant with strength training. The characteristics of the subjects are presented in Table 1. ***[Table 1 about here]*** SCI subjects represent the experimental group (*group E*) and students represent the control subjects (*group C*). SCI subjects were current competitive athletes participating in sports such as wheelchair basketball and wheelchair rugby in the first and second German division and in the national teams, respectively. In the United States wheelchair rugby is commonly referred to as quad rugby. All wheelchair athletes have been performing their team sport at least for 2 years and they train twice to three times per week. They have some experiences with strength training, but primarily with machines and not with free weights or barbell training. Moreover, they were not familiar with regular supervised strength training lasting over a longer period of several weeks. All wheelchair athletes were characterized by variety in classification and motor impairments, whereas two participants were classified as tetraplegic and six as paraplegic. Inclusion criteria of SCI subjects, especially for subjects suffering from tetraplegia, were that they could be able to perform all testing and training conditions (implying to lift a minimum of 20kg in the bench press). None of the control subjects had any physiological or orthopedic limitations that could have affected performance. All subjects were informed about experimental procedures, design of the training, possible risks and benefits of the study. They gave their informed and written consent to take part in the experiment. The investigation was approved by an Institutional Review Board for use of Human subjects. The investigation conforms with the principles outlined in the Declaration of Helsinki developed by the World Medical Association. Exclusion criterion was missing of more than two training sessions.

Procedures

Testing: First, participants were carefully familiarized with all testing procedures in two separate habituation sessions one week before the first measurements. Afterwards, subjects' performances were tested three times: before starting the eight-week training program (pre-test), after finishing the eight-week training period and one week afterwards (post-tests). Best trials of these two post-tests were taken for further statistical analyses.

I. *Measurement device for the registration of power*: We used a bench throw with both arms in a smith machine consisting of a purely concentric movement without an eccentric part. Subjects were asked to throw the barbell as explosive and as high as possible. We analyzed power by measuring maximal velocity (v_{max}) and maximal acceleration (a_{max}) of the barbell using a light sensor (see Fig. 1). ***[Figure 1 about here]*** Moreover, we recorded two time intervals (t1 = first 4mm and t2 = first 8cm of the bench throw) representing the initial acceleration of this ballistic movement. This initial rate of force development in ballistic movements is sometimes called „starting strength“ (Schmidtbleicher in 21).The parameters a_{max}, t1 and t2 were determined from the trial with maximal velocity (v_{max}). The weight of the barbell was about 17 kg. Test-Retest-Reliability of bench throw was calculated in a former study with r= 0.94.

II. *Measurement device for the registration of strength*: a) Maximal strength (F_{max}) and maximal rate of force development (MRFD) were evaluated by measuring force-time curves in isometric condition in bench press (see Fig. 2). ***[Figure 2 about here]*** MRFD was determined at the steepest point and F_{max} at the highest peak of the force-time slope. The parameter MRFD was determined from the trial with maximal value for F_{max}. The movement was concentric without an eccentric part (see above) and subjects were instructed to contract as fast and forcefully as possible against the static barbell. We determined a Test-Retest-Reliability between r=0.92 and r=0.97 for (F_{max}) and r=0.72 to r=0.84 for MRFD in different former studies.

All signals in condition **I** and **II** were recorded with a 1000Hz analog-to-digital conversion rate.

III. *One repetition maximum* (1RM) and *strength endurance* (SE): In dynamic condition with a free barbell we assessed the 1RM and SE in bench press. We calculated SE by repetitions performed with a weight representing 60% of the individual 1RM. Test-Retest-Reliability constituted up to r= 0.98 for 1RM and SE.

IV. *Sprinting performance*: We tested 10m-sprinting performance in wheelchair athletes using a double light barrier system. Sprints were performed in wheelchairs used in competition. In contrast to test situations **I** to **III** the sprint performance was examined in wheelchair athletes exclusively, due to the fact that in control subjects the habituation effects to wheelchair propulsion are expected to superpose adaptations to strength training. In all testing situations the starting position and performance was standardized for all subjects (group E as well as group C) regarding angles, distance between sternum and barbell, as well as starting position in sprinting. The individual positioning and the order of tests were identical in pre- and post-testing. Moreover, subjects were strapped at the hip with a security belt in tests **I** to **III** to avoid bouncing or arching of the back and further auxiliary movements. All subjects were able to perform these tests accurately.

After 15 minutes of warming-up followed by some preconditioning trials, each subject performed five trials with maximal voluntary effort in each test. Best trials were taken for further statistical analyses.

Training: In strength training there are three main methods to increase strength and power: the maximal effort method, the repeated effort method and the dynamic effort method. The maximal effort method is characterized by a magnitude of resistance that is closed to 1RM with 1-3 repetitions in each series. This method is believed to improve both intramuscular and intermuscular coordination and to achieve greatest strength increments. But due to high intensities there is also a “high risk of injuries” (37). The repeated effort method is based on intensities representing approximately 80% of 1RM that are performed in 8 to 12 repetitions “with sincere exertions to failure” (37). This method induces strength enhancement and muscle hypertrophy primarily. But it has to be pointed out that these training effects are always connected with an improvement of relative strength and therefore with improvements of power abilities (see 21, p. 384). The dynamic effort method is used not for increasing maximal strength but only to improve the rate of force development and explosive strength. Athletes using this training method perform fast movements against intermediate resistance.

We chose the repeated effort method in the present study due to the fact that most subjects were not familiar with high intensity strength training with free weights. This training method is associated with a relatively low injury risk. The subjects participated in an eight-week program consisting of hypertrophy-oriented strength training performed twice per week for a total of 16 sessions. Training exercise was bench press. In each session 5 sets were performed while loads ranged from 10 to 12 repetitions representing approximately 80% of 1RM. Rest intervals ranged from 3 to 5 minutes. The weight was increased every time a subject exceeded 12 repetitions. All workouts were surveyed and supervised. Moreover, verbal encouragement was provided in all workouts. Subjects in both training groups refrained from participating in any type of resistance exercises of upper extremities outside the domain of this study. None of the participants were taking any medications or anabolic steroids known to affect resistance exercise performance.

Statistical analyses: Descriptive statistical methods were used to calculate percentage values, means and standard deviations for all dependent variables. A 2 (group) x 2 (time) analysis of variance with repeated measures was used to identify differences between pre- and post-tests and between groups. Subsequent Scheffé post hoc tests were used to determine pairwise differences when significant F ratios were obtained. A student's t-test was calculated to analyze differences between pre- and post-testing in sprint performance in wheelchair athletes. The $p \leq 0.05$ criterion was chosen for establishing the level of significance for all tests (software: SPSS 17.0).

Results

Overall, both groups achieved very similar results: In all parameters we measured improved performance in post-testing – in wheelchair athletes as well as in control subjects. But the level of significance was not reached in all pre-post comparisons. Regarding percentages in most strength and power parameters wheelchair athletes showed a tendency to higher profit from strength training used in this study.

Table 2 represents all results in absolute values in pre- and post-testing in both groups. In the following figures results are expressed as percentage values to improve comparability of data.

I. In power parameters assessed using bench throw in smith machine we found improved performances in both groups. Maximal velocity (v_{max}) increased in *group E* (p= 0.148) as well as in *group C* (p=0.203) about 4.2%. Therefore, comparison of groups demonstrated no significant differences (p=0.997). In maximal acceleration (a_{max}) we found a significant enhancement in *group E* about 24.6% (p=0.041) but no significant pre-post changes in *group C* (+5.9%, p=0.397). Comparison of groups showed again no significant differences (p=0.131) – see Fig. 3. ***[Figure 3 about here]***

Parameters representing the initial acceleration of the ballistic movement in bench throw (t1 = first 4mm and t2 = first 8cm) demonstrated a tendency to reduced time intervals but the level of significance was not reached, whether in *group E* nor in *group C*. Wheelchair athletes improved in t1 (-19.8%, p=0.138) and in t2 (-11%, p=0.084). Control subjects showed similar results in t1 (-7.4%, p=0.164) and in t2 (-3.5%, p=0.157). Accordingly, we calculated no significant variations in analyses of group differences concerning training effects (p=0.216 in t1 and p=0.126 in t2) - see Fig. 4. ***[Figure 4 about here]***

II. Maximal strength (F_{max}) and maximal rate of force development (MRFD) exerted in static condition rose significantly with training in both groups. In group E we found an improvement in F_{max} of 31.6% (p=0.001) and in control group of 15.5% (p=0.041). Once again, there was no significant difference in training adaptations between groups (p=0.077). In MRFD we calculated a significant group difference (p=0.010) as wheelchair athletes demonstrated an impressive enhancement of 71.5% (p=0.021), whereas control subjects improved significantly but less clearly (+8.8%, p=0.301) - see Fig. 5. ***[Figure 5 about here]***

III. Influences of strength training on parameters assessed in dynamic conditions were comparable to results performed in static condition. We proved increased weights lifted in the bench press exercise in post-testing concerning *one repetition maximum* (1RM) in *group E* (+38.6%, p=0.001) as well as in *group C* (+18.5%, p=0.021). Comparison of group differences demonstrated a significant advantage for wheelchair athletes (p=0.043). Regarding number of repetitions with 60% of 1RM, representing *strength endurance* (SE), we observed a significant rise in both groups, whereas in group E the pre-post difference was about 78% (p=0.004) and in group C about 57% (p=0.000). The statistical analyses of group differences resulted once again in no statistically relevant divergence (p=0.324) - see Fig. 6. ***[Figure 6 about here]***

IV. In 10m-sprinting wheelchair athletes improved their performance about 6.2% but the level of significance was failed closely (p=0.058) - see Fig. 7. ***[Figure 7 about here]***

Discussion

In the context of this paper we could not discuss general effects of strength training concerning morphological contributions and adaptations in neuromuscular coordination in detail (see e.g. 14, 21, 22 and more recently 11). But improvements observed in the present study implicate a potential of enhanced inter- and intramuscular coordination. Neural adaptations should dominate morphological adaptations as the training period lasted for only 8 weeks. In most parameters we hypothesized an enhanced efferent neural drive leading to optimized innervation of motor units with a more synchronized discharge behavior and an increased firing rate of motoneurons.

However, our data indicate that wheelchair athletes and physical education students obtained similar effects of heavy resistance-training on strength and power properties in upper extremities. This result is interesting as some authors and coaches speculated about minor adaptation capacities to training exercises in SCI-subjects in general. Some wheelchair athletes participating in the present study had a spinal cord injury at the level of the cervical vertebrae leading to impairments affecting functional abilities of upper extremities. One subject performed 195N (approximately representing 20kg) in F_{max}, for example. Nevertheless, all subjects achieved clear improvements in nearly all parameters.

It is difficult to compare these results with data from the literature as we are not aware of any reports demonstrating effects of comparable training regimes on power and strength parameters in wheelchair athletes. Most studies cope with strain of daily activities and rehabilitation of patients to maintain a certain level of physical activity and promoting functional independence. It seems that these experiments "have focused on rehabilitation from an overall health perspective" (2) primarily. Accordingly, they used moderate intensities in exercises like wheelchair ergometer, kayak ergometer, hand cycling, arm cranking, and circuit training. These training regimes are limited comparable to strength training used in the present study. Selected studies will be presented in a brief overview:

In a study using hydraulic resistance training in SCI subjects lasting 9 weeks the maximum exercise power output increased about 36.7% (5). Davis and Shephard (8) entitled their paper "*Strength training for wheelchair athletes*" but exercise on forearm ergometer was characterized by an endurance effort. In fact, the training stimulus implied "aerobic nature of activity" with intensities of 40% or 70% of maximal oxygen intake lasting 20 or 40 minutes per session (8, p. 25). 16 inactive subjects with spinal lesions performed this training for 16 weeks (three days per week) leading to rise in average power of shoulder extension and elbow extension. Dallmeijer et al. (7) demonstrated improved maximal isometric strength due to quad rugby training lasting 6 months. But subjects were not assigned to strength or resistance training and significant effects were merely found in group of untrained subjects, whereas subjects with higher skill level showed no significant change in maximal strength. Duran and co-workers (9) observed an increase in weight lifted in bench press exercise about 46%. The SCI patients performed various exercises for 16 weeks. And circuit training for 12 weeks on a multi station gym system and on arm ergometer increased strength significantly in SCI patients. These improvements ranged from 12 to 30% (18). Hicks et al. (15) used arm ergometer and circuit training as well, but training was performed for 9 months with subjects ranging from 19 to 65 years. The wide variety of exercises, most with moderate intensities, led to increase in strength ranging from 19% to 34% in each muscle tested. Furthermore, kayak ergometer training was proved to enhance shoulder muscle strength in SCI patients. But the training regime for 10 weeks was again designed as endurance training lasting 60 minutes each session (3). In a recent study dealing with circuit training for 4 months strength improvements ranged from 38.6% to 59.7% for all testing maneuvers. Shortcomings of this experiment were that only seven middle aged men (ranged from 39 to 58 years) with SCI participated and no control group was implied (24). In summary, SCI subjects showed in longitudinal studies enhancement in strength due to training exercises. But „it appears to be impossible to compare the effects on muscle strength between the few studies with available data, because of large differences in tested muscle groups and test methods" (30, p. 327).

Moreover, there are obvious differences in training intensities, training duration, exercises, and participating subjects regarding their classification of impairments and motor skill level. Haisma et al. (13, p. 646) pointed out that "large variability in results found in paraplegia may be attributed to (…) study population".

In the present study we observed improvements in all parameters, whereas similar results were achieved in both groups. In discussion of this item it is to be mentioned that training and most testing conditions were similar regarding concentric movement, starting positions, and angles used in elbow and shoulder. As SCI subjects had no substantial experience with resistance training we chose hypertrophy-oriented strength training with an intensity representing approximately 80% of one-repetition maximum. One can assume that training with the method of maximum explosive strength actions moving high weight-loads (>90% of 1RM) might lead to even greater effects on power and strength parameters such as maximal acceleration in bench throw, as well as maximal strength and maximal rate of force development (MRFD) in static condition. In MRFD we demonstrated a prominent and significant difference between wheelchair athletes and control subjects (see Fig. 5). Besides "real" effects of strength training and despite of habituation sessions before pre-tests, we speculate about stronger learning and habituation influences on testing situation in these subjects. We measured MRFD in static condition in which subjects were instructed to contract as explosively as possible against an insurmountable resistance. It seems that wheelchair athletes learned to perform this task by using adequate neuromuscular coordination and optimized muscle synergies, especially in tetraplegic subjects who have impairments in neuromuscular control of upper extremities. Additionally, one can speculate about the influence of changed composition of muscle fibers in SCI subjects. Due to augmented and permanent use of upper extremities in daily activities, it is hypothesized that some type II fibers have changed to type I fibers in these subjects. Therefore, stimuli of resistance training could have led in percentage to stronger improvements in wheelchair subjects. But conclusive evidence is missing in this topic. Moreover, it is to be emphasize that wheelchair subjects already differ significantly in MRFD in pre-testing to control subjects (p=0,022). Despite the fact that there is no significant difference in pre-testing between groups in other parameters than MRFD, stronger improvements in post-testing in control subjects are explainable by their lower level in strength and power (see Tab. 2).

Few studies addressed the importance of strength and power in upper extremities in wheelchair sports. Tupling et al. (28) demonstrated that initiation of wheelchair movement depends, besides starting technique, on upper extremity strength. In addition Janssen et al. (19) proved a positive correlation between strength and sprinting performance. Moreover, a significant contribution of strength of upper extremities to wheelchair basketball performance was described in the literature (36). In the present study we demonstrated improved sprinting performance at short distance that is relevant in wheelchair basketball and wheelchair rugby (quad rugby). Sprinting time decreased in average by 6.2%. Despite the fact that the level of significance was failed closely for this parameter (p=0.058) one can speculate about a positive influence of enhanced power and strength on performance in these sports. Thus, it seems that resistance training of upper extremities may be beneficial for sprinting in wheelchair sports.

In general, one expects limited training adaptations in SCI-patients with tetraplegia or paraplegia due to their impaired physiological capacity (26, 31, 2, 32, 13). But we already demonstrated that wheelchair athletes, performing wheelchair basketball and rugby, achieved in average similar results in strength and power testing compared to physical education students (29). Data of the present experiment demonstrate at least in principle the adaptation potential in strength and power in these subjects.

However, the results could not be generalized without any constraints. On one hand only 8 wheelchair athletes participated in this study. At the beginning of the study 12 wheelchair athletes participated but 4 subjects were unable to complete all training sessions and withdrew from the study. On the other hand results of SCI-subjects showed strong inter-individual variations due to different impairment classification (32, 25, 29) depending primarily on the completeness of lesion, lesion level, training status, and time since injury (30). Therefore, effects of strength training could be very heterogeneous. Otherwise, Hicks and colleagues observed that „there was no effect of lesion level on the magnitude of strength changes“ (15, p. 38). One can summarize the matter in accordance with Haisma et al. (13, p. 646): "Because of lack of homogeneity, no consistent conclusions on the influence of a particular protocol can be drawn" in SCI-subjects and wheelchair athletes. However, despite the small sample size and inter-individual variability of results our data suggest that wheelchair athletes could enhance their strength and power generation of upper extremities by using strength training comparable to elite athletes.

Shoulder pain is another topic in SCI subjects. More than two thirds of patients reported shoulder pain since beginning of wheelchair use (6). It is known that the upper extremity pain in SCI subjects is due to muscle imbalance at the shoulder joint. And these subjects have a higher risk of shoulder impingement syndrome (1). Nash et al. (24) proved reduced shoulder pain in combination with improved strength. Therefore, the application of adequate resistance training in wheelchair athletes can be addressed in prevention and rehabilitation of shoulder pain syndromes as well.

Practical Applications

The major findings of the present study are on one hand that wheelchair athletes demonstrated significant improvements in strength and power parameters due to resistance training and on the other hand that these effects are comparable to control subjects without spinal cord injury. Therefore, we suggest that heavy resistance training should be of increasingly importance in wheelchair sports to enhance performance in competition. Commonly, circuit training, wheelchair ergometer training and hand cycling each with moderate intensities are used in SCI patients to strengthen upper extremities. It has been demonstrated that these training stimuli are effective in patients for rehabilitation and to cope with strain of daily activities. But in athletes performing sports such as wheelchair basketball and wheelchair rugby (quad rugby) we recommend a training regime with barbells as it was used in the present study. The strength training should be performed twice per week consisting of 5 sets while loads range from 10 to 12 repetitions representing approximately 80% of one-repetition maximum. Following commonly concepts of periodization this phase of *muscle hypertrophy* should be followed by a phase of increased intensity and decreased volume called *strength and power phase*. While each of these two training phases (mesocycles) lasts for 8 weeks. All training sessions should be carefully surveyed and supervised as SCI subjects might have difficulties during exercises in stabilizing their upper part of the body due to lack of muscle strength and coordination deficits. Moreover, it is to point out that SCI subjects, especially in tetraplegia, have an impaired thermoregulation capacity compared to able-bodied counterparts caused by impairment of autonomic and somatic nervous system which disrupts sweating and appropriate vasodilation (Shephard 1994, Bhambhani 2002). Therefore, coaches must ensure that training conditions avoid the risk of hyperthermia.

In conclusion, the present study proved that strength training with heavy resistance may provide functional value to optimize performance in competition in individual sports such as wheelchair athletics (e. g. sprinting and throwing) and in team sports such as wheelchair basketball.

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Figure Legends

Figure 1: Measurement device for the registration of movement speed in upper extremities (analyzed parameters: v_{max}, a_{max}, t1, and t2) in a smith machine.

Figure 2: Measurement device for the registration of maximal strength (F_{max}) and maximal rate of force development (MRFD) in upper extremities in isometric condition.

Figure 3: Pre-post comparison in maximal movement speed (left) and maximal acceleration (right) of barbell in the smith machine [Wheelchair athletes ■ (n=8) – control subjects ♦ (n=8)] in percentage. [p-values: $\mathbf{v_{max}}$ pre-post *group E* = 0.148; *group C* = 0.203; comparison of groups = 0.997. $\mathbf{a_{max}}$ pre-post *group E* = 0.041; *group C* = 0.397; comparison of groups = 0.131]

Figure 4: Pre-post comparison in parameter t1 (left) and t2 (right) [Wheelchair athletes ■ (n=8) – control subjects ♦ (n=8)] in percentage - t1 represents time for the first 4mm and t2 for the first 8cm in acceleration of the barbell in the smith machine. [p-values: **t1** pre-post *group E* = 0.138; *group C* = 0.164; comparison of groups = 0.216. **t2** pre-post *group E* = p=0.084; *group C* = 0.157; comparison of groups = 0.126]

Figure 5: Pre-post comparison in maximal strength (left) and rate of force development (right) in isometric condition [Wheelchair athletes ■ (n=8) – control subjects ♦ (n=8)] in percentage. [p-values: $\mathbf{F_{max}}$ pre-post *group E* = 0.001; *group C* = 0.041; comparison of groups = 0.077. **MRFD** pre-post *group E* = 0.021; *group C* = p=0.301; comparison of groups = 0.010]

Figure 6: Pre-post comparison in one-repetition-maximum *(left) and and strength endurance (right)* in dynamic condition [Wheelchair athletes ■ (n=8) – control subjects ♦ (n=8)] in percentage. [p-values: **1RM** pre-post *group E* = 0.001; *group C* = 0.021; comparison of groups = 0.043. **SE** pre-post *group E* = 0.004; *group C* = 0.000; comparison of groups = 0.324]

Figure 7: Pre-post comparison in 15m-sprinting performance of wheelchair athletes ■ (n=8). [p-value pre-post = 0.058]

Tables

Table 1: Characteristics of participating subjects

	height [cm]	weight [kg]	age [years]
wheelchair athletes	181.3 +/-5,8	75.2 +/- 9,8	33.2 +/-10,6
control subjects	182.1 +/-4,16	78.8 +/-6,2	25.4 +/-1,8

Table 2: Absolute values for all parameters in pre- and post-testing (mean +/-standard deviation).

	wheelchair athletes		control subjects	
	pre	**post**	**pre**	**post**
v_{max} [m/s]	2.39 +/-0.25	2.49 +/-0.24	2.82 +/-0.245	2.93 +/-0.203
a_{max} [m/s2]	51.60 +/- 14.12	63.00 +/-17.32	66.28 +/-11.24	69.38 +/-10.49
t1 [ms]	14.40 +/-5.04	11.14 +/-3.65	11.89 +/-2.58	10.75 +/-1.36
t2 [ms]	89.45 +/-16.67	78.45 +/-8.74	80.28 +/-8.47	77.14 +/-5.55
F_{max} [N]	732.50 +/- 113.69	958.17 +/-124.46	895.88 +/-188.25	1010.50 +/-100.56
MRFD [N/ms]	5.72 +/-0.52	9.73 +/-2.89	9.31 +/-1.65	9.94 +/-1.70
1RM [kg]	77.90 +/-17.52	108.50 +/-28.59	89.31 +/-23.89	104.63 +/-25.59
Repetitions in SE	24.8 +/-7.8	41.3 +/-4.8	23.5 +/-2.9	36.8 +/-6.0
Sprint [s]	4.34 +/-0.37	4.26 +/-0.22	x	x