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Characteristics of the Functioning of the Cardio-Respiratory System and Autonomic Regulation in Para-Athletes with Spinal Injury

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Abstract—The functional state in wheelchair basketball players with damage to the vertebral column in the area of T_6–T_{10} and paraplegia was studied. The subjects were 26.6 ± 1.7 years old on average ($n = 9$). Control subjects were disabled persons who led an active life, with a mean age of 44.5 ± 2.6 years ($n = 13$), athletes with a mean age of 24.6 ± 1.3 years ($n = 14$), and healthy physically active men with a mean age of 24.9 ± 0.6 years ($n = 15$). In wheelchair athletes, the body length in the sitting posture, the respiratory volume, and the performance of respiratory tests were increased. These changes in the musculoskeletal apparatus and the systems providing autonomic regulation of motor activity may be regarded as adaptive modifications due to physical training. In the cardiovascular system of para-athletes and its autonomic regulation, attenuation of an increase in the diastolic arterial pressure value induced by injury and an elevation of sensitivity of arterial baroreflex, which had been decreased due to damage to the vertebral column, were observed. These data indicate compensatory processes adjusting the functioning of the cardiovascular system via the mechanisms of baroreflex regulation.

Keywords: parasport, spinal injury, respiratory system, cardiovascular system

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The successes of the Russian Paralympians at the highest level have not only roused the emotions of their supporters but also attracted the interest of the biomedical community in the characteristics of the functioning of their body. How can people facing such troubles with their health attyain such impressive achievements in sport? What are the features of the adaptive-compensatory processes in their body? Studies in this field were started in 2010, when extended medical examinations of Paralympians were initiated. In other countries, similar studies are also only beginning, and we found only one report concerning statistics on injuries [1] in the press by using "parasport" as a key word. However, most para-athletes do not perform at the Olympics level, although the adaptive-compensatory processes in their bodies are similar to those observed in the Paralympians. Functional indices of their bodies need extended analysis.

In the present study, we examined features of the respiratory and cardiovascular systems, as well as the indices of their autonomic regulation in para-athletes who are basketball players with a spinal injury.

EXPERIMENTAL

Nine wheelchair para-athletes playing basketball at the age of 22–38 years with the mean age of 26.6 ± 1.7 years were involved in the study (parasport group). Among them, one person had a history of a wound in the area of T_6, four people suffered from the consequences of a spinal compression fracture (SCF) in the same area, two persons suffered the consequences of SCF in the area of T_8, one person suffered the consequences of SCF in the area of T_9, and one person suffered the consequences of osteomyelitis of the body of the T_7 vertebra. All persons of this group had clinically confirmed paraplegia with impaired sensitivity of the bottom extremities and pelvic organs. The duration of the period after injury was 5–20 years. Prior to being injured, all subjects in this group were advanced athletes in other sports. The control group of disabled persons (injury group) included 13 men aged 29–58 years, with the mean age of 44.5 ± 2.6 years, who led an active life. All of them had SCF in the area of T_{6-10} with paraplegia and impaired sensitivity of the lower extremities and pelvic organs. The duration of the period after injury was 3–25 years. The sport group included 14 healthy men who were football players aged 22–35 years, with the mean age of 24.6 ± 1.3 years, and the control group included 15 young, physically active men aged 23–31 years, with the mean age of 24.9 ± 0.6 years.

The study was performed using a multisystem spiroarteriocardiorhythmograph (SACR) installation [2]. SACR allows simultaneous estimation of the state of the respiratory system, (the indices of quiet breathing), the state of the myocardium (including amplitude and the temporal parameters of the cardiac complex in the standard lead 1), indices of the heart's performance (such as the systolic volume and minute circulatory volume), indices of the finger blood pressure (BP), and the variability of the heart rate and finger BP. The following indices of variability were analyzed: the total power (TP) of the spectra of the heart rate's variability (ms^2); systolic and diastolic BPs (mm Hg^2); the absolute (ms^2 and mm Hg^2) and the relative (%) power of all spectra in the ranges VLF, LF, and HF; and, based on the variability of the heart rate, we calculated indices LF/HF and (VLF + LF)/HF.

Simultaneous recording of the heart rate and finger BP allowed us to measure the value of the sensitivity of the spontaneous arterial baroreflex (SBR) in the real-time mode, which, together with the indices of the spectral variability of the heart rate and finger BP, reflects the state of autonomic regulation of the cardiovascular system [3–5]. Here, we used two methods of assessment of this index, including calculation of the value of the α index, which represents the ratio between the absolute spectral power of the variability of the heart rate and systolic BP, and direct measurement of SBR at the time periods of coherence of the heart rate and systolic BP.

The recording was performed for 2 min in a quiet context and in the sitting position when a spirometric mask was put on in order to reproduce the additional condition for a functional test [6]. The maximum indices of the respiratory system such as lung capacity and Tiffeneau's index were measured during an additional test after the main recording. Additionally, we estimated the functional state of the respiratory system using Stange's and Genchi's tests.

The physical state of the body was estimated using anthropometrical parameters, including body weight, body height in standing and sitting positions, shoulders in diameter, sagittal and frontal pelvis diameters, neck and alvus circumferences, chest circumferences during inspiration and expiration, and circumferences of the shoulder when tense and relaxed. Based on these data, we calculated a weight-height index and the fat content. We also assessed dynamometry data, as well as the values of systolic, diastolic, and pulse BPs, which were measured by the auscultatory method.

Statistical analysis was performed using the Statistica 6.0 software. For assessment of the statistical differences between groups of subjects on the basis of several indices that describe the functioning of one system, we used algorithms of discriminant analysis and calculated Wilks's λ and F values with the respective number of degrees of freedom, which was followed by the calculation of the statistical differences between groups for each index studied. In order to estimate the effect of the combined action of two factors on each variable studied in the four groups, we used two-way analysis of variances (ANOVA) and calculated the F value with the respective number of degrees of freedom using "injury" and "level of physical activity" as factors. The effect of one factor on the value of one index was estimated using one-way ANOVA followed by post-hoc comparison of the mean values using Tukey's test.

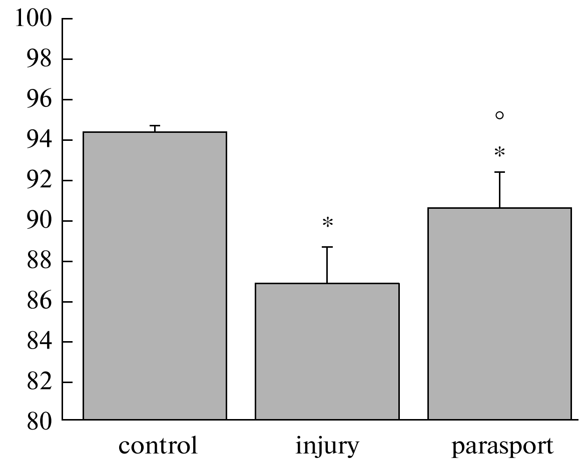

Fig. 1. Body height in the sitting position. Group description; see the Experimental section. Statistical significance of differences according to one-way ANOVA: * $p < 0.05$ and ° $p < 0.05$ compared to the control and injury groups, respectively.

RESULTS

Discriminant analysis of the 16 indices mentioned in Experimental in three groups of subjects, such as control, injury, and parasport indicated the statistical differences between the groups ($\lambda_W = 0.064$, $F_{(32,46)} = 2.749$, $p = 0.003$). However, from all indices, significant differences were revealed in the body height in the sitting position ($F_{(2,46)} = 7.574$, $p = 0.005$), and the subjects from the parasport group significantly differed from those of the control and injury groups ($F_{(32,24)} = 2.657$, $p = 0.033$ and $F_{(32,28)} = 2.326$, $p = 0.054$, respectively). These data show that, in the subjects with injury of the vertebral column, the body height in the sitting position significantly decreased (Fig. 1), although the total body height did not change substantially. In the para-athletes, this index is between the values in the control and injury groups.

Using the set of indices of the respiratory system, including the respiratory volume in the quiet state, the lung capacity, Tiffeneau's index, and Stange's and Genchi's tests, we also revealed statistically significant differences between the control, injury, and parasport groups ($\lambda_W = 0.383$, $F_{(10,46)} = 6.149$, $p = 0.000$). Significant differences were observed in the values of the respiratory volume ($F_{(2,46)} = 4.666$, $p = 0.017$) and performance of Stange's and Genchi's tests ($F_{(2,46)} = 3.556$, $p = 0.041$ and $F_{(2,46)} = 4.664$, $p = 0.017$, respectively). Subjects of the parasport group differed from both the control and injury groups ($F_{(10,24)} = 3.364$, $p = 0.031$

Indices of the respiratory system

Indices	Groups of subjects		
	control $n = 15$	injury $n = 13$	para-athletes $n = 9$
Respiratory volume, L	0.216 ± 0.019	0.201 ± 0.030	0.472 ± 0.129* °
Stange's test, s	86.9 ± 7.9	52.0 ± 6.4	71.6 ± 5.1°
Genchi's test, s	43.3 ± 3.0	25.1 ± 2.2	40.0 ± 3.8°

Note: Statistical significance of differences according to one-way ANOVA: * $p < 0.05$ and ° $p < 0.05$ compared to the control and injury groups, respectively.

and $F_{(10,22)} = 6.244$, $p = 0.002$, respectively). In para-athletes, the value of the respiratory volume was higher and the indices of the performance of the functional tests were between the values for the subject of the other two groups (table). Data on all four groups of subjects demonstrated that the value of the respiratory volume changed depending on both the history of the injury and the level of physical training ($F_{(1,51)} = 4.971$, $p = 0.030$ and $F_{(1,51)} = 46.052$, $p = 0.000$, respectively); moreover, the combined effect of these two factors was revealed ($F_{(1,51)} = 3.802$, $p = 0.057$). Again, wheelchair athletes differed from the other three groups (Fig. 2a), being intermediate between the injury and sport groups.

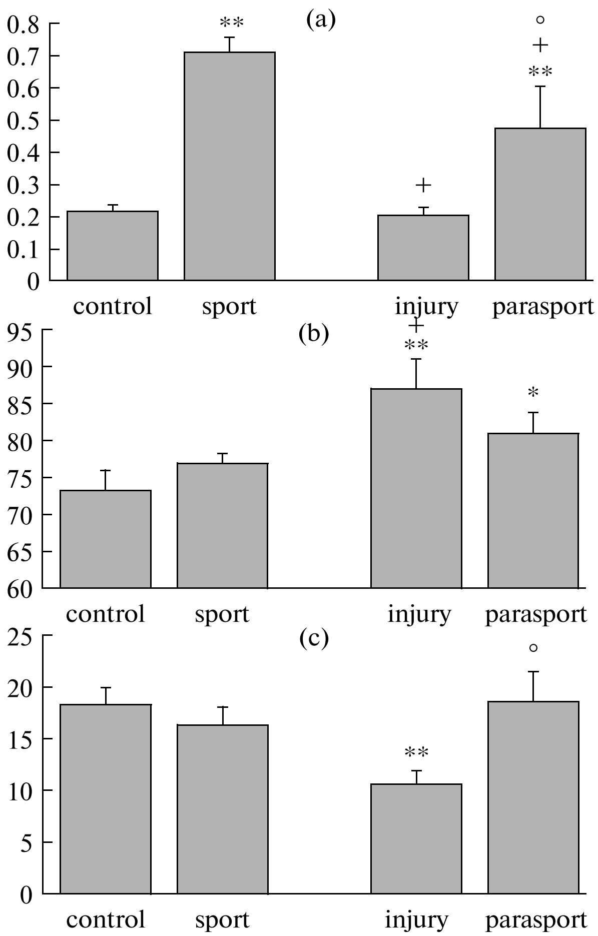

Fig. 2. Values of indices measured in the groups of subjects. (a) Respiratory volume, L; (b) diastolic arterial pressure measured by the Korotkoff's method, mm Hg; (c) sensitivity of spontaneous arterial baroreflex, ms/mm Hg. Group description; see the Experimental section. Statistical significance of differences according to two-way ANOVA: * $p < 0.06$ and ** $p < 0.05$, + $p < 0.05$, and ° $p < 0.05$ compared to the control, sport, and injurygroups, respectively.

Systolic, diastolic, and pulse BPs measured by the traditional Korotkoff's method also had specific features in all four groups ($\lambda_W = 0.698$, $F_{(6,101)} = 2.956$, $p = 0.011$). However, significant differences were observed only in the values of diastolic BP ($\lambda_W = 0.383$, $F_{(2,101)} = 3.047$, $p = 0.038$). We revealed significant differences between the control group and the sport and injury groups ($F_{(6,29)} = 2.591$, $p = 0.086$ and $F_{(6,28)} = 6.955$, $p = 0.002$, respectively), but not between the control and parasport groups ($F_{(6,24)} = 2.175$, $p = 0.125$). ANOVA demonstrated the dependence of the diastolic BP value on the presence of injury ($F_{(1,51)} = 10.125$, $p = 0.002$), but not on the level of physical activity ($F_{(1,51)} = 0.151$, $p = 0.699$). We also found a trend towards the combined effect of these two factors ($F_{(1,51)} = 3.086$, $p = 0.085$). Thus, injury of the vertebral column was followed by an increase in the diastolic BP value. Furthermore, the wheelchair athletes differed from the control and injurygroups, being intermediate between them, but they did not differ from the sport group (Fig. 2b).

We did not find any differences between the groups studied in the values of finger BP or the variability of systolic and diastolic BPs, including the total power of the spectra of the variability of systolic and diastolic BPs, and the absolute and relative power in the ranges VLF, LF, and HF (sixteen indices in total) ($\lambda_W = 0.301$, $F_{(48,101)} = 1.208$, $p = 0.219$). We also did not find any differences between the groups studied in the eight indices of the heart complex and heart performance ($\lambda_W = 0.561$, $F_{(24,101)} = 1.253$, $p = 0.221$).

Discriminant analysis of 14 indices of autonomic regulation of heart activity, including the spectral indices of the variability of the heart rate, such as total spectral power, the absolute and relative powers in the ranges VLF, LF, and HF, and the indices calculated on their basis, and SBR in the subjects of all four groups demonstrated between-group differences ($\lambda_W = 0.231$, $F_{(42,101)} = 2.956$, $p = 0.041$). On the basis of these indices, we observed a significant difference between subjects of the injury group and the para-athletes ($F_{(42,22)} = 2.034$, $p = 0.045$) and a trend towards a difference between the injury and control groups ($F_{(42,28)} = 1.799$, $p = 0.080$). However, a strong trend towards a difference was revealed only in the value of SBR ($\lambda_W = 0.281$, $F_{(2,101)} = 2.392$, $p = 0.085$). ANOVA did not reveal any dependence of the SBR value on the history of the injury or the level of physical activity ($F_{(1,51)} = 1.072$, $p = 0.305$ and $F_{(1,51)} = 1.246$, $p = 0.269$, respectively); however, a trend towards the effect of a combination of these factors was found ($F_{(1,51)} = 3.416$, $p = 0.071$). Post-hoc comparison using Tukey's test showed that the indices in the injury group were significantly lower compared to the control group, whereas the indices in the parasport group significantly differed from those in the injury group and were similar to those observed in the sport and control groups (Fig. 2c).

DISCUSSION

Together with the standard laboratory protocol for the use of a SACR device, spinal injury in the subjects included in this study served as an additional condition for choosing a sitting position for testing. The indices of the cardiovascular system and its autonomic regulation are known to be more sensitive to the subject's position, compared to the subject's age, the level of physical activity, or hypoxia [5]. In our subjects, the sitting position is the main posture in their life.

The location of the damage to the vertebral column in the subjects of the injury and parasport groups lower than T_5 and the clinical picture, including paraplegia and impairments of the sensitivity of the low extremities and pelvic organs, allow us to consider this spinal injury as type-B injury [7]. This type of injury is characterized by the integrity of a segmentary link of autonomic regulation of the respiratory and cardiovascular systems.

It is known that experimental injuries to the spinal cord above the T_3 level are followed by long-term impairments in the functioning of the respiratory system [8, 9], due to damages in the functioning of the respiratory muscles. Impairments in the cardiovascular system, such as tachycardia and a decrease in BP, have also been reported [10]. Furthermore, this type of injury is specifically associated with autonomic dysreflexia [11, 12] in the form of hyperresponsiveness to functional tests and drugs, which reproduce an enhancement of sympathetic activity. Experimental studies have revealed that expression of these changes in the cardiorespiratory system and its autonomic regulation depends on the amount of damage to the spinal cord [13]. Clinical observations under similar conditions demonstrate substantial changes in the heart rate and BP level and a decrease in sympathetic activity with a simultaneous increase in parasympathetic activity [14].

Experimental lesions of the spinal cord located lower resulted in short-term impairments of the functioning of the cardiovascular system, whereas autonomic dysreflexia and attenuated SBR remain to be observed for a long time [15, 16]. In clinical practice, injury of the vertebral column at the level of T_1–L_2 is associated with a decrease in the efficacy of descending sympathetic influences during the acute post-lesion period [17]. Later on, the clinical picture is mainly characterized by an increase in the time delay of baroreflex regulation [18] and autonomic dysreflexia [17].

In our study, we observed a significant shortening of the body height in the sitting position in subjects of the injury group, which, in para-athletes, was compensated due to the development of a muscle corset as a consequence of regular training. An indirect sign of improvement of the functional state of trunk muscles is an increase in respiratory volume in the para-athletes, which is probably related to their better trained respiratory muscles [19]. Damage to the vertebral column above T_3 is known to impair the functioning of the muscles that are responsible for both inspiration and expiration [8]. Chronic lesion- or age-related impairments of the functioning of the spinal cord are followed by decreases in the lung capacity and most other respiratory volumes and capacities [9]. It is evident that, in this process, a substantial role is played by not only spinal damage per se but also the life style of patients, including smoking and low mobility, which results in the development of muscle rigidity and obesity. In our study, out of 13 subjects of the injury group, three men smoked, whereas, in the group of para-athletes, only one subject smoked, although this difference was not significant. Individual data on the smokers did not have any specific features. However, the functional indices of the respiratory system differed substantially. Thus, in the injury group, we observed a decrease in the indices of the respiratory volume and performance of Stange's and Genchi's tests as compared to the control. In contrast, in the parasport group, we found an increase in the respiratory volume and duration of holding of breath in Stange's and Genchi's tests similar to the control. Our data demonstrate compensatory modifications in the respiratory system of the para-athletes related to their intense physical activity.

The close functional relationship between the respiratory and cardiovascular systems suggests the existence of the united cardiorespiratory system of the body. Specifically, the rhythmic work of the respiratory muscles influences the variability of the heart rhythm and BP more than the system of arterial baroreflex [20]. Among the mechanisms of this effect, the enhancement of the sympathetic influence induced by associated respiratory reflexes is emphasized [21]. This, in combination with the mechanisms of arterial baroreflex, synchronizes changes in BP and the heart rate with the phase of the respiratory cycle. Clinical observations demonstrate that spinal injury may modify the parameters of this interaction between the systems. In particular, paraplegia is known to change the spectral parameters of the variability of the heart rate, as the effects of the activation of the sympathetic system at the 0.1-Hz spike in the variability spectra of the heart rate and BP decreases [22] and autonomic dysreflexia is observed [23]. Studies on the cardiovascular system in spinal patients using functional tests suggest that the key step in these modifications of autonomic regulation is impairments in the functioning of arterial baroreflex [24]. In our study, we found that the consequences of spinal injury were expressed as an increase in diastolic BP. This effect was due to metabolic changes in the patient's body rather than neuroautonomic alterations [25], although we did not observe any modifications in the body weight. We suppose that the age of patients might also influence an increase in diastolic BP because the injury group was the oldest group in our study.

We did not find any changes induced by spinal injury in the spectral indices of heart rate variability and finger BP and in the indices calculated based on them, including LF/HF and (VLF + LF)/HF. This was probably due to the performance of the tests using a SACR device in a spirometric mask. This resulted in the redistribution of the spectral indices of the variability of the heart rate to the increased contribution of the HF range [6]. Under these conditions, the differences between groups in the power of the LF range, which includes the frequency of 0.1 Hz and reflects the insufficiency of sympathetic influences in a sitting position, could be masked. We suppose that this was the reason why the only index of autonomic regulation that reflected statistically significant differences between the groups was SBR, characterizing the functioning of arterial baroreflex. We observed a decrease in this index in the injury group and a compensatory increase in this index in the parasport group.

CONCLUSIONS

Our data demonstrate that, in wheelchair athletes, adaptive changes in the state of the musculoskeletal apparatus and the autonomic systems that are responsible for motor activity are related to training. In particular, we observed an increase in the body height in the sitting posture, an elevation of the respiratory volume, and higher efficacy of the performance of functional respiratory tests. Changes in the state of the cardiovascular system and its autonomic regulation may be considered as compensatory and directed to a decrease in lesion-induced elevated diastolic arterial pressure via activation of the mechanisms of the baroreflex, attenuated by damage to the vertebral column.

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