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EFFECT OF FATIGUE ON THE APPEARANCE OF ERRORS IN THE EXECUTION OF A COMPLEX MANUAL TASK – RESEARCH IN THE TABLE TENNIS DOMAIN

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Abstract Although the problem of human fatigue is widely researched, on the basis of detailed research of the literature that was assisted by aggregators such as EBSCO Discovery Service it was determined that there was no paper that previously exclusively dealt with the effect of physical fatigue on the appearance of errors during the execution of a manual task. There are certain papers that deal with the issue of the influence of physical fatigue on motor activity, but they do not take into account in a quantitative way the errors in manual performance that occur as a consequence of fatigue. Besides, some of the papers on similar topics do not quantify fatigue in an adequate way (for example, by using a scale for subjective assessment that is not formally intended to measure fatigue). Due to that, it may be considered that this is the first paper in the world that has been entirely dedicated to the problem of the influence of physical fatigue on errors in the performance of complex manual tasks, such as those in the domain of table tennis. In this research, four intensities of physical activity were chosen to induce fatigue: light, moderate, hard, and very hard. Statistical testing revealed that only when fatigue was induced by light physical activity the number of serving errors was not significantly higher than in the resting state, while fatigue induced by moderate, hard, and very hard physical activity resulted in a statistically significant increase in serving errors. In addition, in this paper for the first time it was calculated the reliability of serving as a ratio of the number of successful serves and the total number of serves. It was found that the reliability of serving (as a complex manual activity) in table tennis decreases by 24.67% overall in the fatigue condition, and specifically by 3.33%, 30%, 28.47%, and 35% when fatigue is induced by light, moderate, hard, and very hard intensity of physical activity, respectively. Having in mind the aforementioned, fatigue should be taken into account when planning and executing intricate and precise manual tasks, such as those in sports, medical procedures, military operations, construction and similar.

Keywords: Fatigue; complex manual tasks; serving; errors; reliability; table tennis.

1. INTRODUCTION

The capacity to perform physical actions can be transiently decreased by muscle fatigue, which can lead to human errors, unsafe actions, productivity loss, injuries, and work-related musculoskeletal disorders [1]. Due to fatigue, the performance of employees can be negatively impacted, leading to a decrease in safe decision-making, shorter attention spans, memory impairment, and reduced reaction time and accuracy [2]. In many work-related settings, fatigue is a significant and relevant factor [3].

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In different industries, physical fatigue is highly prevalent and one of the most important occupational hazards [4]. Due to fatigue, about 40% of workers are regularly exposed to a risk level that is three times higher [2].

Certain modifications to movement patterns and muscle recruitment occur to counteract the effects of muscle fatigue. Highly skilled players, for example, adjust their movement patterns and maintain task requirements in terms of spatial accuracy under fatigue conditions by employing opportunistic movement coordination [5]. People adapt their working strategy to compensate for muscle fatigue, which involves changing movement patterns, recruiting different muscles, and altering the kinetic or kinematic components of the movement, such as joint angles and velocities [1]. There is potential for long-term injury as a result of performing in a state of fatigue. When generating motor skills in a state of fatigue, immediate performance adjustments occur [3]. In one research, half of the respondents exhibited less fluid movement during lifting due to fatigue, with some parts having higher acceleration values and others lower, resulting in more impulsive movements [1]. During intensive manual handling tasks, more vigilant and attentional resources are needed for the highly controlled limbs [6].

All elements of the motor system, from suprasegmental centers to a reduction in the activity of contractile proteins, can produce fatigue [7]. Due to fatigue, performance decline is contributed by a variety of identified mechanisms. The traditional explanation, which involves the accumulation of intracellular lactate and hydrogen ions that impair the function of contractile proteins, is likely of limited significance in mammals. Alternative explanations include the impact of ionic changes on the action potential, various mechanisms leading to the failure of SR Ca2+ release, and the influence of reactive oxygen species [8].

Intense, repeated muscle usage results in a performance decline [8]. In the express industry, repetitive manual packaging tasks result in reduced muscle activity in the brachioradialis, upper trapezius, and erector spinae muscles [9]. Muscle fatigue, which can induce changes in motor coordination, movement stability, and kinematic variability, may be caused by performing repetitive manual tasks [10]. One research [11] has shown that while arm-shoulder fatigue makes nailing and sawing tasks more difficult, it doesn’t impact the performance of sawing or screwing.

2. GOAL OF THE RESEARCH

Although considerable research has been conducted on the issue of human fatigue, a thorough examination of the literature, utilizing comprehensive aggregators such as EBSCO Discovery Service, has revealed a lack of previous scientific papers exclusively addressing the impact of physical fatigue on the occurrence of errors during the execution of manual tasks. While numerous studies explore the impact of physical fatigue on motor function, they do not determine quantitatively errors in manual performance caused by fatigue. In addition, some papers related to similar topics do not employ a suitable quantitative method to measure fatigue (for example they use a subjective assessment scale unsuitable for fatigue measurement). Consequently, it can be argued that this paper represents the first study with the goal of exploring the relationship between physical fatigue and errors in the performance of complex manual tasks, with an accent on the domain of table tennis.

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3. METHOD

First of all, it was necessary to choose an adequate manual task for the aforementioned purpose. In connection with that, it should be pointed out that playing table tennis competitively provides great agility work, coordination, and cardio [12]. The game involves quick reflexes and precise movements, making it a challenging and engaging sport. The motion trajectories of spinning table tennis balls can be significantly influenced by different strokes and speeds [13]. Given its size and weight, the speed at which a table tennis ball can travel is quite remarkable. A ping-pong ball can achieve speeds of up to 113 km per hour [14]. In addition, as tested by the Chinese National Team, the table tennis ball can reach a maximum of 150 revolutions per second [15].

Learning to serve with a lot of rotation in table tennis is a challenging, primarily manual task. It takes a lot of time and practice to become proficient at serving with a lot of rotation in table tennis. Players start by practicing the serve, slowly increasing the amount of rotation as they become more experienced. With practice, players can develop an accurate and consistent serve with enough spin to be successful. This could take a year or more. In table tennis, a “short serve” refers to a serve where the ball, after bouncing on the server’s side, would bounce twice or more on the receiver’s side if left untouched. This type of serve is used to limit the receiver’s options, making it harder for them to attack the ball aggressively. In other words, if a server is using a short serve, he/she does not allow the receiver to play a forehand or a backend spin, because the hand will hit the table. Serving a quality short service is a very demanding and complex manual task. Taking into account all the aforementioned, in this research for the complex manual task it was chosen the task of performing short serves in table tennis. Although serving in table tennis represents a complex manual task, it does not influence the appearance of fatigue, especially if it is about a short series of several serves. Figure 1 shows the area where the ball should fall in order to qualify the serve as accurate.

Figure 1. Performing a short serve in function of a complex manual task and the area where a ball should fall in order to qualify a serve as accurate.

The second issue that was needed to solve was how to induce physical fatigue. Although physical fatigue is possible to induce in various ways (running is one of the examples that was used in many

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research), we estimated that the best way to cause fatigue, in this case, is to choose a task that is connected with table tennis activity. In choosing the appropriate activity for the aforementioned purpose the authors of this paper have had much experience. The first author of this paper was a representative of Serbia in table tennis and a multiple champion of Serbia in all categories. The second author is still actively involved in table tennis. After consultations, we chose interval training with a table tennis robot as a task for the induction of fatigue. Interval training with a table tennis robot is a very demanding physical activity. A robot can eject balls very quickly and frequently. In such a case, a table tennis player is forced to respond fast. Due to that, fatigue can appear very soon, in a period of one or a few minutes, depending on the state of the physical condition of a player. Figure 2 shows the initial task of table tennis players.

Figure 2. Using a robot in the task of induction of physical fatigue in table tennis players.

The third issue that we had to solve was the measurement of physical fatigue induced by the robot. For this purpose, one of the main constraints was the possibility of measuring workload and fatigue in real-time. Although many methods can be used to evaluate fatigue, only several methods are possible to use in real-time in the case of table tennis. The main reason is that forehand and backend top spin are movements that require the use of the entire body, from legs, trunk, arms, up to the neck. Given that, using wire electrodes was not a practical solution. Using subjective measures for fatigue estimation is one of the possible solutions in this case. However, we wanted to choose one of the measures that could objectively measure physical strain and fatigue.

It is well known that heart rate is a good predictor of physical effort. In addition, an important indicator for the evaluation of physical fatigue was found to be heart rate [16]. Heart rate variability (HRV), derived from electrocardiograms and controlled by the autonomic nervous system, has been demonstrated by the study [16] to be a promising indicator for physical fatigue estimation. Additionally, the study found that the selected HRV features, including mean HR, NN50, SDANN, HRVTi, TINN, aVLF, sampen, SD2, SD1/SD2, α, and α1, were effective in assessing physical fatigue. In [17], heart rate was also used as an indicator of physical fatigue. The study found that induced physical fatigue caused a statistically significant change in the average heart rate and heart

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rate variability measures SDNN and RMSSD. The study evaluated heart rate as one of the cardiovascular parameters for physical fatigue assessment. Heart rate measurements, in workers in the industry, were also used as a basis for measurement of physical fatigue [4]. The authors of the previously mentioned paper also mentioned that heart rate was used as a measure of fatigue in many previous researches [18-25].

The aforementioned studies indicate that heart rate, in addition to the estimation of physical strain, is also a good indicator of estimating physical fatigue. Due to that, we used mean heart rate as an indicator of the level of fatigue induced by physical activity (session with the table-tennis robot), and to control fatigue after the session of intense physical work – i.e. during the serving period.

The level of physical exertion and the fatigue induced by it was the next step to be addressed. In this regard, the focus was primarily on the submaximal level of physical exertion. According to [26], for the endurance type of activity, there are several areas of intensity of physical activity, which may vary from very light to maximal. Our goal was to induce light, moderate, hard and very hard physical activity by using a table tennis robot. According to [26], light physical activity involves an area of 50-63% of HR_{max}, moderate area corresponds to 64-76% of HR_{max}, hard physical activity is in the area of 77-93% of HR_{max}, while very hard physical activity is in the area between 94-99 of HR_{max}. Here HRmax indicates the maximum heart rate that the subject can achieve depending on age. This value can be calculated using different formulas. We opted for the formula HR_{max} = 220 - Age.

Considering the above, the testing procedure consisted of the following. The subject's task in the first session consisted of the precise execution of a short, rotated service to a previously marked part of the table tennis table. The basic criterion for the service to be recognized as correct was that the ball bounced at least twice on the opponent's side of the table (which is also proof that the service was short). In the second session, which was related to inducing fatigue in the subjects, the desired intensity of physical activity, light, moderate, or hard, was caused by using a table tennis robot that was mounted on a specially prepared table tennis table for that purpose. The frequency of throwing balls by the robot was adjusted, in order to achieve the desired level of physical activity and induce fatigue. The robot threw long balls across the surface of the table, and the subjects' task was to play a forehand or backhand top spin without interruption, depending on whether the robot threw the ball onto the left or right surface of the table tennis table. The pulse level was continuously measured and evaluated using a device for remote measurement of the pulse level. The duration of the second session was determined individually for each subject, depending on the desired level of physical activity and fatigue that needed to be induced. After the appropriate level of physical activity light, moderate, hard, or very hard was reached and induced corresponding fatigue, the subject would quickly move to the table without the robot and immediately started the third session, which consisted again of performing a short rotating serve that was directed to the previously mentioned part of the table. As in the previous two, the heart rate level was continuously measured in the third session as well. Each subject performed 10 serves in the first and third sessions. The examiner's task was to monitor the respondent's pulse level in all three sessions in accordance with the described procedure and to assess the correctness of each individual service. The serve performance time in both sessions was not limited, but the respondents were instructed to perform the serves one after the other without delay after the first serve. During the serving phase in which the subjects were fatigued (third phase of the experiment), the heart rate did not drop more than 5 % for any respondent in relation to the mean

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heart rate during the phase of inducing fatigue (second phase of the experiment). The serving balls were within arm's reach of the subjects.

The study involved 30 participants. All respondents have been playing table tennis on a regular basis for more than three years and have undergone the necessary training in a table tennis club. The age of respondents ranged from 14 to 55 years. The average age of respondents was 33.5 years (s.d. equals 14.4 years). The examiner was a person with extensive experience in the field of table tennis and completed courses in the field of ergonomics. A V-989 Table Tennis Robot was used to induce fatigue. For continuous heart rate monitoring, a device for remote heart rate monitoring by CatEye (heart rate monitor with wireless heart rate sensor) was used. Before the start of the test, the subjects were rested.

4. RESULTS

The results of the research are presented in Tables 1-4. Table 1 shows the results related to a fatigue session where light physical activity was induced. The labels used in the table are as follows:
RHR – resting heart rate
THRZ – target heart rate zone
HRF – heart rate during the fatigue session
NCSR – number of correctly performed serves immediately after the resting period
NCSF - number of correctly performed serves immediately after physical activity intended to induce fatigue.

Table 1. Data relevant and connected to light physical activity and fatigue induced as a result of this kind of physical activity.

The ordinal number of respondents	Mean RHR	THRZ	Mean HRF	NCSR	NCSF
1.	79	102-129	111	7	6
2.	89	101-127	123	7	6
3.	51	98-123	114	10	10
4.	76	98-123	119	9	8
5.	59	97-122	99	8	9
6.	60	96-120	118	9	9

Table 2 shows the results related to a fatigue session where moderate physical activity was applied.

Table 2. Data relevant and connected to moderate physical activity and fatigue induced as a result of this kind of physical activity.

The ordinal number of respondents	Mean RHR	THRZ	Mean HRF	NCSR	NCSF
1.	85	131-156	132	7	3
2.	99	131-156	142	9	7
3.	68	128-152	144	10	5
4.	60	126-150	133	8	5
5.	72	118-141	124	9	6
6.	68	118-141	136	10	7
7.	64	125-148	126	9	8

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Table 3 shows the results related to a fatigue session where the hard intensity of physical activity was applied.

Table 3. Data relevant and connected to hard physical activity and fatigue induced as a result of this kind of physical activity.

The ordinal number of respondents	Mean RHR	THRZ	Mean HRF	NCSR	NCSF
1.	83	158-191	162	7	5
2.	77	158-191	172	8	6
3.	90	158-191	168	5	2
4.	89	145-175	148	9	6
5.	75	142-171	150	7	5
6.	69	135-163	144	10	5
7.	82	135-163	144	9	8
8.	68	132-160	136	9	8
9.	72	131-158	144	9	6
10.	84	130-157	146	8	4
11.	79	129-155	144	6	6
12.	64	129-155	154	8	1
13.	87	142-172	166	8	4

Table 4 shows the results related to a fatigue session where a very hard intensity of physical activity was applied.

Table 4. Data relevant and connected to very hard physical activity and fatigue induced as a result of this kind of physical activity.

The ordinal number of respondents	Mean RHR	THRZ	Mean HRF	NCSR	NCSF
1.	88	165-173	168	10	5
2.	84	156-166	166	7	3
3.	77	156-166	166	8	5
4.	72	154-163	154	10	8

5. ANALYSIS OF RESULTS

Bearing in mind that the goal of this research is to determine the existence of a difference between the number of errors when performing a complex manual activity in conditions without fatigue and in conditions when fatigue is present, at the beginning we will test the hypothesis that the number of errors in serving when there is fatigue is less than or equal to the number of serving errors when physical fatigue does not exist. To this end, we will use the data on correct services presented in the NCSR and NCSF columns in Tables 1-4, taking into account all 30 respondents. Considering that the test was performed twice with the same subjects, the paired t–test for checking the hypothesis will be used.

Assumptions concerning the paired t-test will be checked at the beginning. The assumption regarding normality was checked based on the Shapiro-Wilk Test (α=0.05). It is assumed that after fatigue minus before fatigue does follow the normal distribution (p-value is 0.4418), or more accurately, we can't reject the normality assumption. The outliers' detection method was Tukey Fence, k=1.5. The

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data doesn't contain outliers. The test priori power is strong, 0.8483. Results of the paired t-test indicated that there is a significant large difference between before fatigue ($M = 8.3$, $SD = 1.3$) and after fatigue ($M = 5.9$, $SD = 2.1$), $t(29) = 7.4$, $p < .001$. The p-value equals 1.7e-8 ($P(x \leqslant -7.45) =$ 1.7e-8). It means that the chance of a type I error (rejecting a correct H_0) is small: 1.658e-8 (0.0000017%). The smaller the p-value the more it supports H_1. In other words, the sample average after fatigue is smaller than before fatigue, and the difference is big enough to be statistically significant. The test statistic T equals -7.45, which is not in the 95% region of acceptance: $[-1.7, \infty]$. The after minus before (-2.47), is not in the 95% region of acceptance: $[-0.56, \infty]$. The 95% confidence interval of after fatigue minus before fatigue is: $[-\infty, -1.9]$. The observed effect size d is large, 1.36. This indicates that the magnitude of the difference between the average of the differences and the expected average of the differences is large. All this means that the number of errors in serving after fatigue was statistically bigger than before fatigue, and the difference is significant.

After this analysis, we should perform the same analysis individually for all chosen areas of the intensity of physical activity and consequently induced fatigue. To this end, first, we will test the hypothesis that the number of errors in serving when there is fatigue induced by light physical activity is less than or equal to the number of serving errors when physical fatigue does not exist. For this purpose, we will use the data presented in Table 1. Considering that the test was performed twice with the same subjects, the paired t–test for checking the hypothesis will be used like in the previous case.

Assumptions concerning the paired t-test will also be checked at the beginning of this analysis. The assumption regarding normality was checked based on the Shapiro-Wilk Test ($\alpha=0.05$). It is assumed that after light fatigue minus before fatigue does follow the normal distribution (p-value is 0.1071), or more accurately, we can't reject the normality assumption. The outliers' detection method was Tukey Fence, k=1.5. The data doesn't contain outliers. Results of the paired t-test indicated that there is a non-significant small difference between before fatigue ($M = 8.3$, $SD = 1.2$) and after light fatigue ($M = 8$, $SD = 1.7$), $t(5) = 1$, $p = .363$. The p-value equals 0.36, ($P(x \leqslant -1) = 0.18$). It means that the sample difference between the averages of after light fatigue and before fatigue is not big enough to be statistically significant. The test statistic T equals -1, which is in the 95% region of acceptance: [-2.57, 2.57]. The after light fatigue minus before fatigue (-0.33), is in the 95% region of acceptance: [-0.86, 0.86]. The 95% confidence interval of after light fatigue minus before fatigue is: [-1.19, 0.52]. The observed effect size d is small. All this suggests that the number of errors in serving after light fatigue was not statistically significantly bigger than before fatigue.

Now we will test the hypothesis that the number of errors in serving when there is fatigue induced by moderate physical activity is less than or equal to the number of serving errors when physical fatigue does not exist. For this purpose, we will use the data presented in Table 2. Considering that the test was performed twice with the same subjects, the paired t–test for checking the hypothesis will be used like in the previous cases.

Assumptions concerning the paired t-test will be checked at the beginning. The assumption regarding normality will be checked based on the Shapiro-Wilk Test ($\alpha=0.05$). It is assumed that after moderate fatigue minus before fatigue does follow the normal distribution (p-value is 0.9219), or more accurately, we can't reject the normality assumption. The outliers' detection method was Tukey

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Fence, k=1.5. The data doesn't contain outliers. Results of the paired t-test indicate that there is a significant large difference between before fatigue (M = 8.9, SD = 1.1) and after moderate fatigue (M = 5.9, SD = 1.7), t(6) = 6.1, p < .001. The p-value equals 0.00085, (P(x⩽-6.15) = 0.00042). It means that the chance of a type I error (rejecting a correct H_0) is small. In other words, the sample difference between the averages after moderate fatigue and before fatigue is big enough to be statistically significant. The test statistic T equals -6.15, which is not in the 95% region of acceptance: [-2.45, 2.45]. The after moderate fatigue minus before fatigue (-3), is not in the 95% region of acceptance: [-1.19, 1.19]. The 95% confidence interval of after moderate fatigue minus before fatigue is: [-4.19, -1.81]. The observed effect size d is large, 2.32. This indicates that the magnitude of the difference between the average of the differences and the expected average of the differences is large. All this means that the number of errors in serving after moderate fatigue was statistically bigger than before fatigue, and the difference is significant.

Now we will test the hypothesis that the number of errors in serving when there is fatigue induced by hard physical activity is less than or equal to the number of serving errors when physical fatigue does not exist. For this purpose, we will use the data presented in Table 3. Considering that the test was performed twice with the same subjects, the paired t–test for checking the hypothesis will be used like in the previous cases.

Assumptions concerning the paired t-test will be checked at the beginning. The normality assumption was checked based on the Shapiro-Wilk Test (α=0.05). It is assumed that after hard fatigue minus before fatigue does follow the normal distribution (p-value is 0.676), or more accurately, we can't reject the normality assumption. The outliers' detection method was Tukey Fence, k=1.5. The data doesn't contain outliers. Results of the paired-t test indicated that there is a significant large difference between before fatigue (M = 7.9, SD = 1.4) and after hard fatigue (M = 5.1, SD = 2), t(12) = 5.5, p < .001. The p-value equals 0.00014, (P(x⩽-5.51) = 0.000068). It means that the chance of a type I error (rejecting a correct H_0) is small:0.0001351 (0.014%). In other words, the sample difference between the averages after hard fatigue and before fatigue is big enough to be statistically significant. The test statistic T equals -5.51, which is not in the 95% region of acceptance: [-2.18, 2.18]. The after hard fatigue minus before fatigue (-2.85), is not in the 95% region of acceptance: [-1.13, 1.13]. The 95% confidence interval of after hard fatigue minus before fatigue is: [-3.97, -1.72]. The observed effect size d is large, 1.53. All this means that the number of errors in serving after hard fatigue was statistically bigger than before fatigue, and the difference is significant.

Finally, we will test the hypothesis that the number of errors in serving when there is fatigue induced by very hard physical activity is less than or equal to the number of serving errors when physical fatigue does not exist. For this purpose, we will use the data presented in Table 4. Considering that the test was performed twice with the same subjects, the paired t–test for checking the hypothesis will be used like in all the previous cases.

Assumptions concerning the paired t-test will be checked at the beginning. The normality assumption was checked based on the Shapiro-Wilk Test (α=0.05). It is assumed that after very hard fatigue minus before fatigue does follow the normal distribution (p-value is 0.676), or more accurately, we can't reject the normality assumption. The outliers' detection method was Tukey Fence, k=1.5. The data doesn't contain outliers. Results of the paired t-test indicated that there is a significant large

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difference between before fatigue (M = 8.8, SD = 1.5) and after very hard fatigue (M = 5.3, SD = 2.1), t(3) = 5.4, p = .006. The p-value equals 0.0062, (P(x⩽-5.42) = 0.0062). It means that the chance of a type I error (rejecting a correct H_0) is small: 0.006154 (0.62%). The test statistic T equals -5.42, which is not in the 95% region of acceptance: [-2.35, ∞]. The after very hard fatigue minus before fatigue (-3.5), is not in the 95% region of acceptance: [-1.52, ∞]. The 95% confidence interval of after very hard fatigue minus before fatigue is: [-∞, -1.98]. The observed effect size d is large, 2.71. All this means that the number of errors in serving after very hard fatigue was statistically bigger than before fatigue, and the difference is significant.

Now we will perform an analysis of the reliability of serves in conditions without fatigue, and in conditions when fatigue is induced among players. For that purpose, we will suppose that the elements of the quality of serves, such as rotation and the height of the bounce of the ball are the same in conditions without and with fatigue (these aspects were controlled by the experimenter, and they were estimated as identical). We will calculate reliability as the ratio of the number of accurate serves to the total number of serves. The criteria when a serve was considered accurate were mentioned earlier in the paper. In that way, by calculating the proportion of serves that successfully land where it was predicted by the task and the overall number of serves, we can assess the reliability of this complex manual task. This procedure for the determination of the reliability of services was not applied earlier in the scientific literature.

For this purpose, data regarding NCSR and NCSF in tables 1-4 will be used in calculations. For each subject, reliability of serving is calculated as $R_{ri} = \frac{NCSR_i}{N}$ for the state without fatigue, and as $R_{fi} = \frac{NCSF_i}{N}$ for the state with fatigue (N is the number of trials and amounts 10). For example, for the respondent with ordinal number 1 in Table 1, R_{r1} = 0.7, while R_{f1} = 0.6.

Now we want to determine the average reliability of serving in the state without fatigue $\overline{R_{ro}}$ and in the state with fatigue $\overline{R_{f0}}$, taking into account all respondents (here N=30). We can calculate them according to the formulae $\overline{R_{ro}} = \frac{\sum R_{ri}}{30}$ and $\overline{R_{f0}} = \frac{\sum R_{fi}}{30}$. After the calculations we get $\overline{R_{ro}}$ = 0.8333 and $\overline{R_{f0}}$ = 0.5866. So, in relation to the reliability of serving in the condition without fatigue, the overall reliability of serving is 24.67% less in the condition of fatigue.

Now we want to determine the difference in the reliability of serving in relation to the state before fatigue for each selected fatigue zone, that is after light, moderate, hard and very hard physical activity. First we will do it for light physical activity (Table 1). Using the procedure as above, we get

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$\overline{R_{rl}}$ = 0.8333 and $\overline{R_{fl}}$ = 0.8. So, in relation to the reliability of serving in the condition without fatigue, the reliability of serving in the condition of light fatigue is 3.33% less.

Now we want to determine the difference in the reliability of serving between the state before fatigue and the state of fatigue that was caused by moderate physical activity. For that purpose we will use the data in Table 2. Using the same procedure, we get $\overline{R_{rm}}$ = 0.8857 and $\overline{R_{fm}}$ = 0.5857. So, in relation to the reliability of serving in the condition without fatigue, the reliability of serving in the condition of moderate fatigue is less by 30%.

Now we will determine the difference in the reliability of serving between the state before fatigue and the state of fatigue that was caused by hard physical activity. For that purpose we will use the data in Table 3. Using the same procedure, we get $\overline{R_{rh}}$ = 0.7923 and $\overline{R_{fh}}$ = 0.5076. So, in relation to the reliability of serving without fatigue, the reliability of serving in the condition of hard physical fatigue is 28.47% lower.

Finally, we will determine the difference in the reliability of serving between the state before fatigue and the state of fatigue that was caused by very hard physical activity. For that purpose we will use the data in Table 4. Using the same procedure, we get $\overline{R_{rvh}}$ = 0.875 and $\overline{R_{fvh}}$ = 0.525. So, the reliability of serving in the condition of very hard physical fatigue is 35% lower than the reliability of serving in the condition without fatigue.

6. DISCUSION

It should be noted that there was no significant difference in heart rate in the resting period and the session with performing serve immediately after the resting period. Also, it should be mentioned that THRZ was calculated for each participant and each session in accordance with the classification of the intensity of physical activity that has been given in [26]. In addition, it should be noted that in all cases of checking the hypotheses by the paired t-test for light, medium, hard and very hard physical activity, the priori power was low, due to the relatively small number of subjects in the selected groups. However, the results of testing clearly indicate the trend of the increasing number of errors in a task connected with complex manual performance after medium, hard and very hard fatigue.

It should be mentioned that there are at first glance similar researches that examine the influence of fatigue on limb muscle activity, or similar. However, these researches do not use appropriate

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instruments for the subjective assessment of physical fatigue. Such scales can measure the rate of perceived exertion, but not fatigue in a formal sense.

7. CONCLUSION

For the first time, in this paper has been considered the problem of the influence of physical fatigue on the appearance of errors in performing a complex manual task, such as performing a short rotation serve in table tennis. Four intensities of physical activity were chosen to induce fatigue: light, moderate, hard, and very hard. This research has shown that physical fatigue is a factor that influences the performance of complex manual tasks.

Testing of statistical hypotheses has shown that only for fatigue induced by light physical activity, the number of errors in serving was not statistically bigger (based on the application of a paired t-test), than in the condition when the serves were performed without the existence of physical fatigue (resting state). In all other cases, i.e. when the serves were performed in the state of fatigue that was induced by moderate, hard, and very hard physical activity, the number of errors in serving in all those cases was statistically greater than the number of errors in serving that was related to the state without fatigue.

In addition, in this paper for the first time it was calculated the reliability of serving as a ratio of the number of successful serves and the total number of serves. In relation to the reliability of serving in the condition without fatigue, the reliability of serving in the conditions of fatigue was less for:

- 24.67 % in total (taking into account all types of intensity of physical activity for the induction of fatigue – light, medium, hard, and very hard)
- 3.33 % in the case of fatigue induced by the light intensity of physical activity
- 30 % in the case of fatigue induced by the moderate intensity of physical activity
- 28.47 % in the case of fatigue induced by the hard intensity of physical activity
- 35 % in the case of fatigue induced by the very hard intensity of physical activity.

All this indicates that physical fatigue is a factor that influences the appearance of errors in performing complex manual tasks, such as precise rotational serving in table tennis. This factor should be taken into account when performing complex and precise manual tasks, like in sports, medical interventions, military operations, etc. In all cases, it is advisable to take at least a short rest before undertaking any complex and precise manual activity.

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