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Electromyographic Analysis of Elite Para Table Tennis Players with Complete and Incomplete Spinal Cord Injury during Forehand Loop and Backhand

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SUMMARY

Introduction. Para table tennis is a popular sport among individuals with disabilities, and each Paralympic sport has its own classification system. This classification aims to minimize the impact of impairments caused by disability on athletic performance. In the present study, the electromyographic variables of the muscles involved in performing the forehand loop and backhand techniques of elite para table tennis players with complete and incomplete spinal cord injuries in the class 5 category were compared.

Material and methods. A total of 20 male participants who compete at the national level were selected using the convenience sampling method. According to the ASIA scale, the participants were divided into two groups of 10 people. The first group completed spinal cord injury, while the second group had incomplete spinal cord injury. After entering the laboratory, the electrodes were attached to their deltoid, biceps, external oblique, and erector spinae muscles using the SENIAM protocol. After attaching the electrodes, the tasks were performed and muscles' EMG activity, as well as their onset and offset contraction were monitored. For data analysis, the signals were first filtered, then rectified, and the level of muscle activity was measured using the RMS (Root Mean Square) method. In addition, for signal normalization, the submaximal contraction method, which is more suitable for individuals with impairments, was used.

Results. The findings revealed that there are significant differences in the amount of EMG activity as well as the timing of the onset and offset of contraction of selected muscles in two groups of complete and incomplete spinal cord injuries. A significant difference in the deltoid muscle was observed between the two groups during both the forehand loop and backhand movements.

Conclusions. The findings suggest that athletes with incomplete spinal cord injuries may perform better than those in the complete group. However, current para table tennis classification rules place both groups in the same class, which could impact the outcome of matches.

KEY WORDS

Spinal Cord Injury; classification; para table tennis; electromyography; EMG.

INTRODUCTION

Para table tennis is recognized as the third most popular sport in Paralympic competitions with participants from over 100 countries worldwide (1). The International Paralympic Committee's statistics indicate that over 40 million people now compete in this sport globally. The sport's popularity is due, in part, to its inclusivity, allowing athletes with various impairments to participate. Also, this sport is the

fourth most rewarded sport in Paralympic competitions (2). This sport requires complex techniques including acceleration, deceleration, change of direction, quick movements, balance, and stability to generate sufficient force in the athlete's upper limb (3). In para table tennis, rotational movements, speed, and agility are crucial factors that affect a player's performance in a match (3). Due to the type and severity of impairments in people with disabilities, creating movement adaptations is necessary to play para table tennis. Therefore, the biomechanics and force production in these people differ from those without impairments. Individuals with motion impairment or reduced range of motion in the trunk may compensate for this weakness by exerting more force in their arm, elbow, or wrist region (4). In sports such as para table tennis and wheelchair basketball, classification criteria including performance ability and 63 physiological criteria are used (5). These criteria encompass trunk stability, sitting balance, and body displacement in the sagittal, frontal, and horizontal planes (6). Sitting stability is vital in transitions and performance during play (7, 8). Moreover, the control of the trunk muscles is one of the most significant factors -contributing to the control of posture and balance. People with spinal cord injuries may experience impairment or deficiency in controlling trunk and upper limb movements, depending on the severity of their injury. This can lead to functional differentiation among individuals and is taken into account in the classification system for Paralympic sports. The purpose of classification is to ensure fair competition under equal conditions for athletes with similar impairments (9-11). However, there have been concerns about the accuracy of the classification system, with some athletes potentially being placed in the wrong class (11, 12). Para table tennis classification is done at both clinical and technical levels, with participants undergoing medical examinations before being examined for technical classification. During a practice game, participants are evaluated by the classifier based on their performance of various skills such as forehand, backhands, forehand loops, and trunk movements (11). Players may have different performance abilities for different reasons leading to discrepancies in the technical performance of those in the same class (9). If these differences significantly affect the athlete's performance, it can compromise the fairness of the competition. For example, classification in para table tennis class 5 can be challenging and sometimes causes disputes among classifiers. This study focuses on examining participants with spinal cord injuries in sitting class 5. Previous studies have examined biomechanical differences in able-bodied players or compared able-bodied players with those who have impairments in this sport. However, no study has yet investigated EMG (electromyography) differences across various classes of athletes with impairments (13-15). According to the classification rules published in 2018 by the International Table Tennis Federation (ITTF), participants in the sitting class 5 have normal function (range of motion, strength) in the trunk muscles. Also, the pelvic-thigh girdle muscles work optimally and there is no abnormal movement (range of motion, strength) when bending forward and laterally. These players also possess good sitting balance and have spinal cord injury (SCI) levels ranging from the L1 vertebra to the S2 vertebra. According to the American Spinal Cord Injury Association (ASIA), the spinal cord injury of these people can be both complete (complete paralysis of the lower limb) and incomplete (the function of the lower limb is not completely lost but weakened). Based on this, individuals with varying levels of spinal cord injury may be classified in this class, leading to unique challenges (9). The purpose of the present study was to compare the electromyographic variables (EMG activity, onset, and offset) of the muscles involved (deltoid, biceps, erector spinae, external oblique) during the execution of forehand loop and backhand techniques in elite para table tennis players with complete and incomplete spinal cord injuries within class 5.

MATERIALS AND METHODS

Participants

In this study, there were a total of 20 participants who were divided into two groups: one group had complete spinal cord injury (injury type A based on the ASIA scale) and the other group had incomplete spinal cord injury (injury type B or C based on ASIA scale). All participants were professionals in their sport and were competing at a national championship level. Their average age, activity experience, height while seated, and weight were 32.10 ± 5.40 years, 7.15 ± 2.27 years, 85.85 ± 1.87 cm, and 71.5 ± 5.31 kg, respectively. In addition, all participants were right-handed and had 3 regular training sessions per week. The inclusion criteria for this study were male gender, ages between 20 to 35 years, sports experience of more than 5 years, and participation in national championships. The exclusion criteria were any pain during the test in the shoulder, back, or central trunk area, not completing the questionnaire, and not wanting to finish the test session. All methods were carried out in accordance with the Declaration

of Helsinki. Ethical approval was granted by the Instructions of the Biomedical Research Ethics Committee of the University of Tehran, and an ethics code (IR. UT. SPORT. REC.1400.017 – date of approval: January 08, 2021) was obtained. Written informed consent to be involved in the experimental procedures was obtained from all the participants before the start of the study. In this study, convenience sampling was selected.

Research design

After entering the laboratory environment, participants are provided with information about the research and are required to sign a consent form. Their height and weight are measured using a tape measure and scale. The areas where the electrodes need to be connected to the skin are shaved and disinfected with alcohol to minimize skin resistance. The electrodes are then connected to the muscles using the SENIAM protocol (Stegeman & Hermens, 2017), all on the right side of the participants' bodies. Each of the four electrodes is connected parallel to the muscle fibers on the muscle belly, with the correct connection verified through isometric contractions. The biceps muscle electrode is connected between the inner acromion line and the cubital fossa at a distance of one-third of the cubital fossa (16) (**figure 1**). The electrode for the deltoid muscle is connected between the acromion line and the external epicondyle of the elbow on the protrusion of the deltoid muscle (17) (**figure 2**). The electrode of the erector spinae muscle is connected ted two fingers' distance from the L1 vertebra (18, 19). The electrode for the external oblique muscle is connected between the last rib and the ASIS (19, 20) (**figure 3**). After the electrodes are connected, participants are given 10 minutes to warm up their body generally and specifically. The first protocol involves three forehand loops, before to the protocol, participants are allowed to perform 20 forehand loops as a trial to prepare for the test. The second protocol was performed after a 2-minute rest period, and similar to the first protocol, participants performed 20 backhands as a test to adapt to the second protocol. The mean of three backhands for each participant was taken into consideration, and the ball throwing speed remained constant throughout both protocols.

Instruments

Muscle activity was recorded using a 16-channel EMGBTS-free 300 device from Italy, equipped with model surface electrodes made of Ag/AgCl. The sampling frequency was set to 1,000 Hz and MATLAB software (MATLAB R2022b; The MathWorks Inc., Natick, MA, USA) was used to process the data. To determine the onset and offset of muscle activity, each muscle was considered "on" when its amplitude was 3 standard deviation (SD) points above the baseline signal for a 25 ms window. Each muscle was considered "off" when the amplitude dropped below 3



Figure 1. Biceps muscle electrode placement.



Figure 2. Deltoid muscle electrode placement.



Figure 3. Erector spinae muscle electrode placement.

SD points above the baseline signal (15). The feedforward and feedback activity of the muscles were also calculated 300 ms before and after the ball hit the racket, using the mean square root method with a time stability of 50 ms. In this way, the raw electromyography data was first filtered with a 4th order intermediate pass filter with a cutoff of 10 and 500 Hz and then rectified. For the study, a standard Primorac carbon racket with two Acuda S1 turbo was used, along with sixty Donik Coach balls and a fully automatic Robo Pong 540 ball launcher capable of shooting 25 balls per minute (21).

Statistical analysis

The data collected in this study was analyzed using SPSS 27 software. Descriptive statistics were calculated for all variables, including mean and standard deviation (SD). To determine the normality of the data distribution, the Shapiro-Wilk test was performed. In the inferential statistics section, both the parametric independent t-test and the non-parametric Mann-Whitney test were utilized to compare the electromyographic variables. The significance level was set at ≤ 0.05, and the effect size (Cohen's d) was calculated for each test.

Table I. Descriptive data of the participants.

Groups	Number	Age (year)	Height seated (cm)	Weight (kg)	Activity experience (year)
Complete lesion	10	31.30 ± 5.33	86.10 ± 1.91	71 ± 5.90	7.70 ± 2.83
Incomplete lesion	10	32.90 ± 5.65	85.60 ± 5.65	71.30 ± 4.96	6.60 ± 1.50

Table II. Muscle activity of selected muscles in forehand loop and backhand.

Muscles	Groups	Mean ± SD (milliseconds)	T-value	P- value	95% Confidence Interval of the Difference		Effect Size
Muscle activity of selected muscles in forehand loop							
Deltoid	Complete lesion	2.06 ± 28.50	-2.449	0.025	-4.087	-0.313	-1.095
	Incomplete lesion	1.94 ± 30.70					
Biceps	Complete lesion	1.71± 16.60	-14.264	0.0001	-12.735	-9.465	-6.379
	Incomplete lesion	1.76 ± 27.70					
Erector spinae	Complete lesion	1.56 ± 23.30	-13.284	0.0001	-11.118	-8.082	-5.941
	Incomplete lesion	1.66 ± 32.90					
External oblique	Complete lesion	1.79 ± 30.10	-3.781	0.001	-4.823	-1.377	-1.691
	Incomplete lesion	1.87 ± 33.20					
Muscle activity of selected muscles in backhand							
Deltoid	Complete lesion	2.35 ± 31.70	-2.982	0.008	-5.795	-1.005	-1.334
	Incomplete lesion	2.72 ± 35.10					
Biceps	Complete lesion	2.80 ± 23.10	-6.564	0.0001	-8.713	-4.487	-2.935
	Incomplete lesion	1.49 ± 29.70					
Erector spinae	Complete lesion	2.01 ± 26.40	-4.178	0.001	-4.809	-1.591	-1.868
	Incomplete lesion	1.35 ± 29.60					
External oblique	Complete lesion	1.83 ± 32.40	-11.437	0.0001	-10.535	-7.265	-5.115
	Incomplete lesion	1.63 ± 41.30					

*p ≤ 0.05.

Table III. Onset of selected muscles in forehand loop and backhand.

Muscles	Groups	Mean ± SD (milliseconds)	U-value	Z-value	P-value	Effect Size
Onset of selected muscles in forehand loop						
Deltoid	Complete lesion	.34±14.23	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.26±56.25				
Biceps	Complete lesion	.30±22.89	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.62±34.26				
Erector spinae	Complete lesion	.42±44.64	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.37±37.50				
External oblique	Complete lesion	.31±6.36	0.000	-3.781	0.0001	4.364
	Incomplete lesion	.17±43.30				
Onset of selected muscles in backhand						
Deltoid	Complete lesion	.17±15.46	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.23±57.49				
Biceps	Complete lesion	.24±22.03	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.29±36.48				
Erector spinae	Complete lesion	.24±45.12	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.32±37.47				
External oblique	Complete lesion	.24±6.44	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.25±44.42				

*$p \leq 0.05$.

RESULTS

The data presented in **table I** shows the demographic characteristics of the participants, specifically the number of individuals in each group, their age, sitting height, weight, and experience in sports activities. The findings revealed that there is a significant difference for the amount of EMG activity in forehand loop including deltoid ($p = 0.025$), biceps ($p = 0.0001$), erector spinae ($p = 0.0001$) and external oblique ($p = 0.001$) and in backhand including deltoid ($p = 0.008$), biceps ($p = 0.001$), erector spinae ($p = 0.0001$) and external oblique ($p = 0.0001$) in selected muscles between the two groups of complete and incomplete spinal cord injury (**table 2**). Also, according to the obtained results, it was found that there is a significant difference for onset and offset of the selected muscles in the forehand loop including deltoid ($p = 0.0001$), biceps ($p = 0.0001$), erector spinae ($p = 0.0001$) and external obliques ($p = 0.0001$) and in backhand including deltoid ($p = 0.0001$), biceps ($p = 0.0001$), erector spinae ($p = 0.0001$) and external oblique ($p = 0.0001$) between the two groups of complete and incomplete spinal cord injury (**tables III** and **IV**).

DISCUSSION

In the present study, the electromyographic variables of the muscles involved in performing the forehand loop and backhand techniques of elite para table tennis players with complete and incomplete spinal cord injuries in the class 5 category were investigated. Para table tennis athletes in the sitting classes need to coordinate their upper body and trunk movements for executing forehand loop and backhand techniques. Studies have shown that following spinal cord injury, individuals face difficulty in voluntarily controlling their trunk muscles, which can make it challeng-

Table IV. Offset of selected muscles in forehand loop and backhand.

Muscles	Groups	Mean ± SD (milliseconds)	U-value	Z-value	P-value	Effect Size
Offset of selected muscles in forehand loop						
Deltoid	Complete lesion	.35 ± 20.44	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.46 ± 50.07				
Biceps	Complete lesion	.25 ± 34.39	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.25 ± 81.97				
Erector spinae	Complete lesion	.26 ± 37.21	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.36 ± 148.78				
External oblique	Complete lesion	.27 ± 43.48	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.24 ± 87.35				
Offset of selected muscles in backhand						
Deltoid	Complete lesion	.49 ± 71.20	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.33 ± 52.23				
Biceps	Complete lesion	.31 ± 36.28	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.32 ± 82.56				
Erector spinae	Complete lesion	.38 ± 39.67	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.32 ± 151.64				
External oblique	Complete lesion	.26 ± 45.45	0.000	-3.780	0.0001	4.363
	Incomplete lesion	.49 ± 71.20				

*$p \leq 0.05$.

ing for them to perform activities that require coordination between their limbs and trunk muscles (22). For instance, grabbing an object requires the activity of the trunk muscles before or simultaneously with the voluntary movements of the arm (23), which changes in the quality of this function due to spinal cord injury. The rotational movements of the trunk and forward bending during the performance of forehand loop and backhand techniques require the activation of erector spinae and external oblique muscles. The erector spinae is a key muscle for maintaining an upright position and aids in forward and lateral bending as an auxiliary muscle for the anterior trunk muscles (24, 25). Electromyography studies have shown that individuals with spinal cord injuries experience altered EMG activity, onset and offset of the erector spinae muscle in both static and dynamic tasks (26). Van Helden found that the activity level of the erector spinae muscle is reduced in individuals with spinal cord injuries compared to healthy individuals. The results of van Helden's research indicated that due to the nerve defect in the central nervous system resulting from spinal cord injury affects the selective activation of muscles. Selective activation is more affected by the lesion in individuals with complete spinal cord injury than in those with incomplete spinal cord injury (27). In addition, previous studies showed that the feedforward control of the erector spinae muscle is impaired due to spinal cord injury in individuals with spinal cord injuries, which affects the level of activity and the onset and offset of the muscle's contraction (28, 29). According to Santos, trunk muscle strength and trunk balance were significantly different across various wheelchair basketball classes. Higher-class players demonstrated greater strength and balance compared to lower-class players (30). Based on Saltan and Ankarali, the muscle activation was performed using surface electromyography in players with spinal cord injuries for the triceps, serratus anterior, latissimus dorsi, rectus abdominis, external oblique, and erector spinae

muscles. The change in the activation of the rectus abdominis and external abdominal oblique muscles was significantly higher when standing on an unstable surface than on a stable surface, highlighting the importance of central muscles for trunk stability (31). The findings of the present study also showed that there is a difference between the EMG activity and onset and offset of the erector spinae and external oblique muscles in the two studied groups, in such a way that people with complete spinal cord injury have a later onset and earlier offset and less EMG activity. This difference could be due to the complete loss of sensorimotor ability, reduced ability to maintain sitting balance, and reduced neuromuscular control ability in individuals with complete spinal cord injury compared to individuals with incomplete spinal cord injury (8, 22, 32-36). The deltoid and biceps muscles play a significant role in this sport due to the various shoulder and elbow joint movements involved, and coordinated trunk muscle activity is crucial for distal stability and smooth performance. In addition, people using wheelchairs need the coordinated activity of the upper limb muscles, particularly the muscles of the shoulder complex. Wang showed that athletes with different levels of spinal cord injury have different functional activity in the trunk and upper limbs (8). Lee investigated the upper limb muscle activity in individuals with spinal cord injury and those with upper limb muscle weakness (control group). In that study, people with spinal cord injury showed less muscle activity in the upper limb compared to the control group (37). Dany Gagnon showed that the level of spinal cord injury in the signals received from the surface electromyography in the upper limb is effective in transfer movements (38). Hanks examined the biomechanics of wheelchair lacrosse athletes and found that in athletes with spinal cord injury, upper limb biomechanics were significantly different from other wheelchair and standing athletes. The axial rotation of the trunk in the maximum extension of the elbow in the spinal cord injury group was significantly lower than in the standing group. The spinal cord injury group showed less axial rotation of the trunk towards the dominant arm during the hand-back phase and less translational movement towards the non-dominant arm during maximum elbow extension. The decrease in the axial rotation of the trunk in the spinal cord injury group reduces trunk control, and limits rotation in overhead movements, and changes the kinematics of the upper limb in this group. Furthermore, the spinal cord injury group showed a significant decrease in the range of motion of abduction and adduction compared to the sitting and standing group (39). According to the neuromuscular control of the movements, the timing of the onset of muscle contraction is crucial for proper control of trunk and upper limbs movements. In a study by Hanks & Oliver (40), wheelchair basketball players with spinal cord injuries had more activity in their rectus abdominis, latissimus dorsi, anterior deltoid, and triceps muscles compared to healthy individuals. However, research on the onset and offset of muscle contraction in the trunk and upper limbs during para table tennis is limited. According to the findings of this study, it seems that the group with incomplete spinal cord injury had better trunk control, feedforward pattern, sitting balance, and activity pattern than the participants with complete spinal cord injury, so the amount of EMG activity and the onset and offset of muscle contraction in two groups were significantly different. These findings are in line with previous research reports, some of which were mentioned above. This difference in the electromyographic characteristics of these two groups can possibly affect their skill performance while playing para table tennis and facilitate the superiority of the group with incomplete spinal cord injury.

Limitations

It is important to note that certain limitations might have affected the performance and test results of the subjects in this study. These factors were beyond the researchers' control. Firstly, the psychological factors of the participants such as stress, fear of injury, or lack of awareness were not considered in the study. Secondly, confounding factors such as differences in training programs, as well as nutritional and therapeutic differences among participants, were present and could not be controlled in this study. Additionally, this study only included male participants, with the rationale being gender homogeneity and reducing variability in the study results. The findings of this study cannot be generalized to female participants, but future studies could include female participants. Finally, the sample size of this study was limited due to strict inclusion criteria and reluctance of some athletes to participate. Specifically, the study was restricted to athletes with the intended classification who lived in the province where the study was conducted.

CONCLUSIONS

Within this sport, players commonly utilize the forehand loop and backhand techniques. The forehand loop serves as an offensive maneuver for scoring points, while the backhand technique serves as a defensive and attacking strategy. Notably, alterations in muscle activity patterns can significantly impact the execution of these movements, which can lead to enhanced performance for individuals with

incomplete spinal cord injuries during competitive play. The study's results highlight the importance of considering both the extent of injury and level of lesion, as well as the athlete's performance during gameplay, when classifying athletes in this sport. It is recommended that athletes with similar neuromuscular and performance characteristics be placed in the same class, rather than solely focusing on injury level. The study also revealed significant differences in EMG activity and muscle activation timing between para table tennis players with complete and incomplete spinal cord injuries in class 5, with those with incomplete injuries performing better. To improve the classification process, it is suggested that tool-based evaluations be utilized to assess functional and skill-related positions. This approach can lead to a more accurate and fair classification system for athletes in para table tennis.

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DATA AVAILABILITY
Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS
All authors: conceptualization, writing – original draft, writing – review & editing, project administration, data curation.

CONFLICT OF INTERESTS
The authors declare that they have no conflict of interests.

REFERENCES

1. Fuchs M, Faber IR, Lames M. Game characteristics in elite para table tennis. Ger J Ex Sport Research. 2019;49(3):251-8. doi: 10.1007/s12662-019-00575-4.
2. Alghosi M, Karimizadeh Ardakani M, Norouzi M, Hosseinzadeh Z. Epidemiology of sports injuries in para table tennis. J Res Sport Rehabil. 2021;8(16):53-9. doi: 10.22084/rsr.2021.22169.1522.
3. Bańkosz Z, Winiarski S. Using wearable inertial sensors to estimate kinematic parameters and variability in the table tennis topspin forehand stroke. Appl Bionics Biomech. 2020;2020. doi: 10.1155/2020/8413948.
4. De Luigi AJ. Technology and biomechanics of adaptive sports prostheses. Adaptive Sports Medicine: A Clinical Guide: Springer; 2024. p. 35-48.
5. Akınoğlu B, Kocahan T, Yıldırım NÜ, Soylu Ç, Apur U, Hasanoğlu A. A comparison of wrist isokinetic muscle strength in wheelchair table tennis and wheelchair basketball players. Orthop J Sports Med. 2017;5(2_suppl2):2325967117S00068. doi: 10.1177/2325967117S00068.
6. Santos SdS, Alonso AC, Greve JMDA. Quantitative evaluation of trunk muscle strength in wheelchair basketball players. Motriz: Revista de Educação Física. 2016;22:69-72. doi: 10.1590/S1980-6574201600020009.
7. Chow JW, Chae W-S, Crawford MJ. Kinematic analysis of shot-putting performed by wheelchair athletes of different medical classes. J Sports Sci. 2000;18(5):321-30. doi: 10.1080/026404100402386.
8. Wang Y-j, Li J-j, Zhou H-j, et al. Surface electromyography as a measure of trunk muscle activity in patients with spinal cord injury: a meta-analytic review. J Spinal Cord Med. 2016;39(1):15-23. doi: 10.1179/2045772315Y.0000000059.
9. Caldwell M, De Luigi AJ. Wheelchair tennis and para-table tennis. Adaptive Sports Medicine: A Clinical Guide. 2018:201-17.
10. Weikert T, Al-Mohannadi K, Sörling P, et al. International table tennis federation.
11. Tweedy SM, Vanlandewijck YC. International Paralympic Committee position stand—background and scientific principles of classification in Paralympic sport. Br J Sports Med. 2011;45(4):259-69. doi: 10.1136/bjsm.2009.065060.
12. Cassese FP, Raiola G. The importance of sport in disability management. J Sports Sci. 2017;10(Suppl. 1):7-11. Available at: https://www.cabidigitallibrary.org/doi/full/10.5555/20183110805.
13. Bankosz Z, Winiarski S. Using Wearable Inertial Sensors to Estimate Kinematic Parameters and Variability in the Table Tennis Topspin Forehand Stroke. Appl Bionics Biomech. 2020;2020. doi: 10.1155/2020/8413948.
14. Iino Y. Hip joint kinetics in the table tennis topspin forehand: relationship to racket velocity. J Sports Sci. 2018;36(7):834-42. doi: 10.1080/02640414.2017.1344777.
15. Meghdadi N, Yalfani A, Minoonejad H. Electromyographic analysis of shoulder girdle muscle activation while performing a forehand topspin in elite table tennis athletes with and without shoulder impingement syndrome. J Shoulder Elbow Surg. 2019;28(8):1537-45. doi: 10.1016/j.jse.2019.01.021.
16. Liao F, Zhang X, Cao C, Hung IY-J, Chen Y, Jan Y-K. Effects of muscle fatigue and recovery on complexity of surface electromyography of Biceps Brachii. Entropy. 2021;23(8):1036. doi: 10.3390/e23081036.
17. Qassim HM, Hasan WZW, Ramli HR, Harith HH, Mat LNI, Ismail LI. Proposed fatigue index for the objective detection of muscle fatigue using surface electromyography and a double-step binary classifier. Sensors. 2022;22(5):1900. doi: 10.3390/s22051900.
18. Shang W, Wang X, Wei X. Effects of different types of abdominal support on lumbar-back muscle surface electromyography signals in people with abdominal obesity. Chin J Tiss Engin Res. 2022;26(11):1656.
19. Mitchell M, Yarossi M, Pierce D, Garbarini E, Forrest G. Reliability of surface EMG as an assessment tool for trunk activity

and potential to determine neurorecovery in SCI. Spinal Cord. 2015;53(5):368-74. doi: 10.1038/sc.2014.171.
20. Mandroukas A, Michailidis Y, Kyranoudis AE, Christoulas K, Metaxas T. Surface electromyographic activity of the rectus abdominis and external oblique during isometric and dynamic exercises. J Funct Morphol Kinesiol. 2022;7(3):67. doi: 10.3390/jfmk7030067.
21. Xia R, Dai B, Fu W, Gu N, Wu Y. Kinematic comparisons of the shakehand and penhold grips in table tennis forehand and backhand strokes when returning topspin and backspin balls. J Sports Sci Med. 2020;19(4):637.
22. Desroches G, Gagnon D, Nadeau S, Popovic M. Magnitude of forward trunk flexion influences upper limb muscular efforts and dynamic postural stability requirements during sitting pivot transfers in individuals with spinal cord injury. J Electromyogr Kinesiol. 2013;23(6):1325-33. doi: 10.1016/j.jelekin.2013.09.003.
23. Aruin AS, Latash ML. Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. Exp Brain Res. 1995;103:323-32. doi: 10.1007/BF00231718.
24. Moseley GL, Hodges PW, Gandevia SC. Deep and superficial fibers of the lumbar multifidus muscle are differentially active during voluntary arm movements. Spine. 2002;27(2):E29-E36.
25. Bergmark A. Stability of the lumbar spine: a study in mechanical engineering. Acta Orthop Scand. 1989;60(sup230):1-54. doi: 10.3109/17453678909154177.
26. Potten Y, Seelen H, Drukker J, Reulen J, Drost M. Postural muscle responses in the spinal cord injured persons during forward reaching. Ergonomics. 1999;42(9):1200-15. doi: 10.1080/001401399185081.
27. van Helden JF, Cabral HV, Alexander E, et al. Changes in thoracic erector spinae regional activation during postural adjustments and functional reaching tasks after spinal cord injury. 2025;133(3):727-741. doi: 10.1152/jn.00246.2024.
28. Chiou S-Y, Strutton PH. Crossed corticospinal facilitation between arm and trunk muscles correlates with trunk control after spinal cord injury. Front Hum Neurosci. 2020;14:583579. doi: 10.3389/fnhum.2020.583579.
29. Rowland RS, Jenkinson N, Chiou S-Y. Age-related differences in corticospinal excitability and anticipatory postural adjustments of the trunk. Front Aging Neurosci. 2021;13:718784. doi: 10.3389/fnagi.2021.718784.
30. da Silva Santos S, Krishnan C, Alonso AC, Greve JMDA. Trunk function correlates positively with wheelchair basketball player classification. Am J Phys Med Rehabil. 2017;96(2):101-8. doi: 10.1097/phm.0000000000000548.
31. Saltan A, Ankarali H. The role of trunk stabilization in functional-classification levels in wheelchair basketball. J Sport Rehabil. 2017;26(4):287-93. doi: 10.1123/jsr.2016-0054.
32. Castillo-Escario Y, Kumru H, Valls-Solé J, García-Alen L, Jané R, Vidal J. Quantitative evaluation of trunk function and the StartReact effect during reaching in patients with cervical and thoracic spinal cord injury. J Neural Eng. 2021;18(4):0460d2. doi: 10.1088/1741-2552/ac19d3.
33. Chow JW, Millikan TA, Carlton LG, Chae W-s, Lim Y-t, Morse MI. Kinematic and electromyographic analysis of wheelchair propulsion on ramps of different slopes for young men with paraplegia. Arch Phys Med Rehabil. 2009;90(2):271-8. doi: 10.1016/j.apmr.2008.07.019.
34. Gagnon D, Nadeau S, Gravel D, Noreau L, Larivière C, McFadyen B. Movement patterns and muscular demands during posterior transfers toward an elevated surface in individuals with spinal cord injury. Spinal Cord. 2005;43(2):74-84. doi: 10.1038/sj.sc.3101660.
35. Louis N, Gorce P. Surface electromyography activity of upper limb muscle during wheelchair propulsion: Influence of wheelchair configuration. Clin Biomech. 2010;25(9):879-85. doi: 10.1016/j.clinbiomech.2010.07.002.
36. Milosevic M, Yokoyama H, Grangeon M, et al. Muscle synergies reveal impaired trunk muscle coordination strategies in individuals with thoracic spinal cord injury. J Electromyogr Kinesiol. 2017;36:40-8. doi: 10.1016/j.jelekin.2017.06.007.
37. Lee K-S, Zaman M, Hwang J. Reduced Muscle Activity of the Upper Extremity in Individuals with Spinal Cord Injuries. Int J Environ Res Public Health. 2022;19(8):4708. doi: 10.3390/ijerph19084708.
38. Gagnon D, Nadeau S, Noreau L, Eng JJ, Gravel D. Electromyographic patterns of upper extremity muscles during sitting pivot transfers performed by individuals with spinal cord injury. J Electromyogr Kinesiol. 2009;19(3):509-20. doi: 10.1016/j.jelekin.2007.12.005.
39. Hanks MM, Schnorenberg AJ, Lee KK, Slavens BA. Upper Extremity Biomechanical Differences between Wheelchair Lacrosse Athletes with Spinal Cord Injury and Able-Bodied Lacrosse Athletes during Overhead Throwing. Am J Phys Med Rehabil. 2023 April;1(1024):365-71. doi: 10.1097/phm.0000000000001989.
40. Hanks M, Oliver G. Muscle activation patterns in wheelchair basketball athletes with and without physical disability. Int J Physiatry. 2018;1:4-13. doi: 10.23937/2572-4215.1510013.