ORİJİNAL ARAŞTIRMA ORIGINAL RESEARCH

DOI: 10.5336/sportsci.2016-54361

Motion Adaptive Electromechanical Delay Measurement: Flatwater Kayak Stroke Implication

Harekete Uyumlu Elektromekanik Gecikme Ölçümü: Durgunsu Kayak Kürek Çekişi Uygulaması

Eren KAYA,[a]
İsmail BAYRAM,[b]
Ali Onur CERRAH,[b]
Hayri ERTAN[b]

[a]Department of Mechanical Engineering,
Anadolu University Faculty of Engineering,
[b]Anadolu University
Faculty of Sport Sciences,
Eskişehir

Geliş Tarihi/*Received:* 26.12.2016
Kabul Tarihi/*Accepted:* 13.04.2017

Yazışma Adresi/*Correspondence:*
Eren KAYA
Anadolu University Faculty of Engineering,
Department of Mechanical Engineering,
Eskişehir,
TURKEY/TÜRKİYE
erenkaya10@gmail.com

This study was presented as oral announcement at "The 10th International Conference in Physical Education, Sports and Physical Therapy-ICPESPT 2016", 18-20 November 2016, Elazığ, Turkey.

ABSTRACT Objective: Electromechanical delay (EMD) is a substantial component of athletic performance as it is potent in reactive time and power production. A novel EMD measurement method was applied during flatwater kayak stroke in this study. In flatwater kayaking, stroke rate (number of strokes per minute, tempo), which may be increased by lower EMD, is a major parameter in boat speed. The purpose of this study is to investigate EMD in catch phase of flatwater kayak stroke. **Material and Methods:** A male and a female kayak athlete volunteered to participate the study. Kayak stroke was conducted on kayak ergometer. Muscle activation onset and mechanical response was assessed by electromyogram (EMG) and 3-axis accelerometer, respectively. EMG sensors were placed on M. Latissimus Dorsi (LD), M. Pectoralis Major (PM), Anterior Deltoid (AD) and Posterior Deltoid (PD). The accelerometer was placed on fifth metacarpophalangeal joint. EMD was calculated as the latency between EMG onset and accelerometer onset. **Results:** Two data recordings, which were 20 seconds long for each subject, were ensured. The EMD values calculated for the male and female subject's LD were 51.25 ms±3.01 and 61.13 ms±2.94; and PD were 37.25 ms±3.57 and 49.37 ms±4.43 ms, respectively. **Conclusion:** The findings of this study conducted during dynamic kayak stroke elicit results in spectrum of reported EMD values in clinical studies. With use of the present method, EMD for various sports and movement patterns may be investigated.

Keywords: Electromechanical delay; flatwater kayak; EMG; accelerometer; stroke rate

ÖZET Amaç: Elektromekanik gecikme (EG) reaktif süre ve güç üretiminde etkili olduğundan, sportif performansın önemli bir bileşenidir. Bu çalışmada, durgunsu kayak kürek çekişi esnasında özgün bir EG ölçüm yöntemi uygulanmıştır. Durgunsu kayak sporunda, daha düşük bir EG ile arttırılabilecek olan dakikada kürek çekiş sayısı (tempo), tekne süratine etki eden önemli bir parametredir. Bu çalışmanın amacı, EG nin durgunsu kayak kürek çekiş hareketi giriş fazında incelenmesidir. **Gereç ve Yöntemler:** Bir erkek ve bir kadın kayak sporcusu çalışmaya katılmaya gönüllü olmuşlardır. Kayak hareketi, kayak ergometresi üzerinde gerçekleştirilmiştir. Kassal aktivasyon başlangıcı elektromiyografi (EMG) ile mekanik yanıt ise 3 eksenli akselerometre ile belirlenmiştir. EMG sensörleri; M. Latissimus Dorsi (LD), M. Pectoralis Major (PM), Anterior Deltoid (AD) ve Posterior Deltoid (PD) üzerine yerleştirilmişlerdir. Akselerometre beşinci metakarpofalangeal eklem üzerine yerleştirilmiştir. EG; EMG ve akselerometre başlangıcı arasındaki gecikme olarak hesaplanmıştır. **Bulgular:** Her bir katılımcı için 20 saniyelik iki veri kaydı sağlanmıştır. Hesaplanan EG süresi erkek ve kadın denekte, sıra ile, LD için 51,25 ms±3,01 ve 61,13 ms±2,94; PD için ise 37,25 ms±3,57 ve 49,37 ms±4,43 ms olarak hesaplanmıştır. **Sonuç:** Dinamik kayak kürek çekiş hareketi sırasında gerçekleştirilen analizin bulguları, klinik araştırmalar sonucunda bildirilen EG değerleri aralığında bulunmuştur. Bu yöntemin kullanılması ile çeşitli spor branşlarında ve hareket örüntülerinde EG incelenebilecektir.

Anahtar Kelimeler: Elektromekanik gecikme; durgunsu kayak; EMG; akselerometre; kürek çekiş sayısı

The time lapse between the onset of detectable electrical activity of a muscle and the associated mechanical output during muscular contraction is defined as electromechanical delay (EMD).[1] EMD has been shown to be influenced by electrochemical processes (synaptic transmission, action potential propagation across the sarcolemma, excitation-contraction coupling), mechanical processes (force transmission along the series elastic components, position and stiffness of the contractile and elastic components) and muscle fiber type composition.[2] Therefore, EMD analysis may offer useful information about post-synaptic events that affect the function of skeletal muscle following an intervention or training protocol.[3]

Shorter EMD would yield muscle torque in lesser time, which means a shorter reaction time and in turn a quick joint stability. Reduced reaction time would ensure a higher degree of reactive agility and power production which are substantial parameters of athletic performance. As various joint injuries occur from rapid force changes in joint structure, quick joint stability may prevent possible joint injuries.[4]

EMD analyses have been employed in various conditions, such as under eccentric and concentric contractions, in analysis of muscle neuromechanical properties, during isometric and isokinetic contractions, following neuromuscular training, in clinical studies about joint disorders, in comparing age and gender effects to EMD.[1,3,4,5-7] As far as we know, EMD values reported in literature resides between 8.5 ms during supramaximally stimulated tibial nerve and 127.5 ms during voluntary contraction.[7,5] In electrically stimulated contraction conditions, cortical inputs are bypassed and force output is observed in shorter duration than voluntary elicited contraction.[8]

In various sports biomechanical studies; complex dynamic motion, which means multiple joints, planes, angles including various muscular contraction types, is investigated. EMD has been widely investigated and shown to be a measure with a high degree of reliability by various experimental measurement designs.[9] Recently published studies used different methods such as ultrasound and custom programmed algorithms to detect EMD.[10-12] To our knowledge, however, there is no previous study aimed to ensure EMD assessment during motion adaptive conditions, which would allow multiple measurement possibilities (multi angular, multi planar, multi muscular) and mobility freedom for the subject instead of experiment design specific measurements. We hypothesized that determination of muscular onset component of the EMD by a wireless accelerometer sensor may ensure motion adaptive conditions.

Flatwater kayaking stroke was thought to be a convenient and practical motion for EMD analysis. The aim of the flatwater kayaking is to cover the race distance in least possible time and passing the finish line before the rivals. The forward kayak stroke cycle comprises aligned contralateral pushing and pulling movements done by upper extremity coordinated with lower extremity pedal movements and torso rotation.[13,14] In biomechanical flatwater kayak analysis, the stroke is divided into four phases; (1) the catch, characterized initially by horizontal blade position and end with fully submerged blade into the water, (2) the pull, begins blade being fully buried into the water and ends with blades contact with air, (3) the exit, the action from blade's contact with air to horizontal position in the air, (4) recuperation, preparation for the next stroke which will take place on the other side of the boat.[15] Four phases of the kayak stroke is shown in Figure 1. We hypothesized that per-

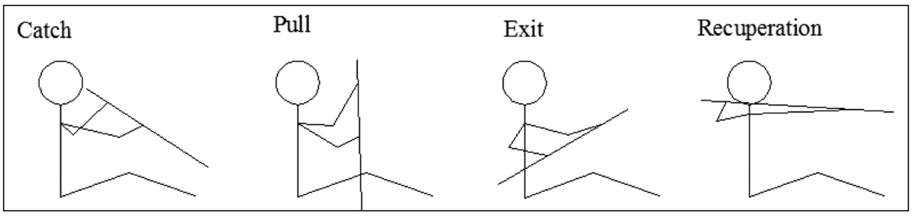


FIGURE 1: Phases of flatwater kayak stroke.

forming an EMD analysis at the beginning of the catch phase would render possible to measure realistic EMD values as muscular inhibition during recuperation phase in various muscles precedes catch phase.

The kayak speed, consequently the kayak performance, is determined by the magnitude and shape of the paddle force (propulsive force transmitted to water via paddle) - time curve.[16,17] Stroke rate is the number paddle strokes performed per minute, ranging between 80 and 140 depending race distance and individual. Accordingly, stroke rate is a key component in kayak velocity and considered one of the major biomechanical predictors of flatwater kayak performance.[18,19] Gomes et al. reported that; with higher stroke rates, force-time curve of a kayak paddle becomes more rectangular shaped rather than triangular shaped.[20] This results from increase of mean to peak force ratio, and, therefore, kayak paddlers should seek a high stroke rate for optimal boat velocity. It can be concluded that, as reaction time is directly affected by EMD, reduction of EMD in phases of the kayak stroke may increase stroke rate, therefore boat speed. In literature, there is no research on EMD values in flatwater kayak sport.

The aim of this study is two fold; (1) to develop a motion and athlete adaptive EMD measurement system which means minimal restriction to dynamic motion patterns, (2) to measure EMD in flatwater kayak stroke's catch phase.

MATERIAL AND METHODS

SUBJECTS

One male and female subject both of whom are international level kayak athletes volunteered to participate the study. They were healthy subjects without any known injury, metabolic or neurologic disease. Physical and anthropometric characteristics of the subjects are given in Table 1. The subjects are requested not to drink caffeine or similar beverages in the 24 hour and abstain from strenuous physical activity in 48 hours preceding the test. All the experimental procedures were conducted in accordance with the principles of the 1975 Helsinki Declaration. The subjects read and signed a detailed consent about the study. All procedures conducted in the experiment were approved by Anadolu University Ethics Committee (Approval Protocol Number: 27444).

EXPERIMENTAL DESIGN

The kayak stroke is performed on an air-braked, drag adjustable kayak ergometer (Dansprint, Hvidovre, Denmark). Both of the subjects have reported to be familiar with the kayak ergometer as they have used kayak ergometers extensively in land training. The distance from seat to foot-bar and hand position of the carbon shaft were adjusted to match each individual's seat position in kayak and on water paddle position, respectively. To simulate on water drag forces due to body mass displacement, ergometer's flywheel damper was adjusted for body mass. Control of the exercise intensity and stroke rate were ensured by real time monitoring of power output per stroke (W) and stroke rate (strokes.min^{-1}) on ergometer's data monitor.

The assessment of electrical onset was determined by sampling the electric activity of target muscles using a double differential EMG system (Delsys, Trigno Wireless EMG System, Boston, USA: 20-450 Hz signal bandwidth, signal gain=909, CMRR>80 dB, baseline noise< 750 nV). The EMG data were unilaterally recorded from dominant side of the subjects from the muscles as follows: Pectoralis Major (PM), Latissimus Dorsi (LD), Anterior Deltoid (AD) and Posterior Deltoid (PD). The skin preparation and electrode placement procedures were completed according to SENIAM (Surface Electro MyoGraphy for the Non-Invasive Assessment of Muscles) recommendations. Before the measurements, signal was visually inspected to minimize

TABLE 1: Physical and anthropometric characteristics of the participants.

	Male Participant	Female Participant
Age (years)	27	28
Weight (kg)	78	68
Height (cm)	178	167
BMI	24.6	24.3
Kayak Experience (years)	8	10

background noise and remove any unwanted DC offset. The EMG signal was sampled at a frequency of 2000 Hz with respect to previous recommendations.[21]

Mechanical onset of muscles, which means joint action was assessed by a 3-axis accelerometer sensor (Delsys, Trigno Wireless System, Boston, USA: 50 Hz signal bandwidth, gain=20dB/dec, baseline noise <0.0025 g) and a measurement range of ±1.5 g was specified to ensure a better sampling resolution (0.016 g/bit). Accelerometer sensor was placed on fifth metacarpophalangeal joint of the dominant side of the subjects to detect the beginning of the catch phase and acceleration data were sampled at a frequency of 150 Hz. EMG and accelerometer synchronization was also ensured as they were connected to a common data logger.

Before the test, an individual warm up period of 3-5 minutes on kayak ergometer was performed by the athletes. Then, the subjects were requested to gradually reach their %60 of the 1000 meter race parameters (paddling intensity and stroke rate). They were also asked to hold that paddling intensity and stroke rate for 20 seconds for data collection. They were then allowed to rest for about 5 minutes before the next trial. A total of two trials were applied for each subject. Following the test, when the subjects were verbally questioned about the ergometer paddling test, they responded that the paddling feeling was very similar to on water kayaking.[22]

DATA ANALYSIS

All the raw data collected were transferred to Matlab R2015a (Licensed to Anadolu University, Mathworks, Massachusetts, USA) for data analysis. Raw EMG data for each subject were first full wave rectified. Then, a 2nd order low pass Butterworth filter with a 20 Hz cut off frequency was applied for signal smoothing. The accelerometer data consisted of three axes (x, y, z), so root mean square of these data was calculated for each sample point to get resultant accelerometer data. Then, the resultant accelerometer data was filtered with a 4th order low pass Butterworth filter (10 Hz cut off frequency).

EMD was calculated as the time lapse between electrical onset (EMG threshold) and mechanical onset (accelerometer threshold). The detection of EMG onset and accelerometer onset is shown in Figure 2. The EMG and accelerometer onset was detected by a statistically optimal decision algorithm where window size and standard deviation

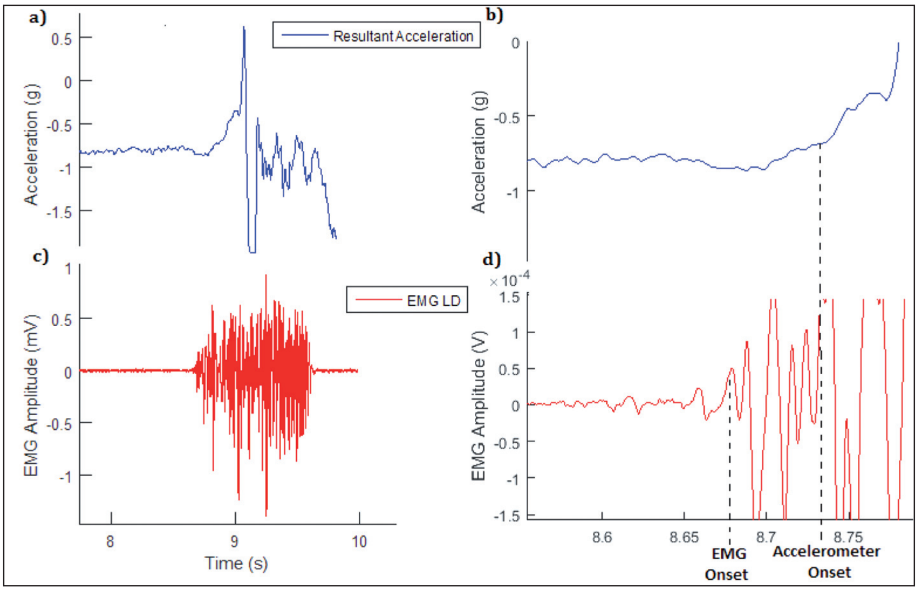


FIGURE 2: Signals for one stroke **a)** Accelerometer signal between 7.8-10 s, **b)** Accelerometer signal between 8.55-8.80 s **c)** EMG signal between 7.8*10 s **d)** EMG signal between 8.55-8.80 s.

EMG: Electromechanical delay.

coefficient were 25 ms and 3, respectively.[24] This means that computer algorithm calculated mean signal amplitude for each following 25 points and if this value is above 3 standard deviations of the baseline signal (resting period), then this point was accepted as threshold (onset point).

EMD of the LD and PD at the beginning of the catch phase were calculated for each subject using each stroke data during two measurements and reported as mean and standard deviation, since they are primarily agonist muscles in catch phase initiation.[15] PM and AD signal data were also processed to crosscheck the co-activation relationship between LD and PD, during catch phase. Because, inhibition of PM and AD is expected at the beginning of the catch phase, as they are antagonists of the LD and PD, respectively. As one of the main purposes of this study was to investigate the inter muscular relationship, the latency between EMD of the LD and PD (Δt LD - PD) was also calculated.

STATISTICAL ANALYSIS

All statistical analysis were conducted using Minitab 17 (Licensed to Anadolu University, Minitab Inc, Pennsylvania, USA) with a significance level established as $p<0.05$. Measures of centrality and spread were presented as mean ± standard deviation. Normality distribution of the dependent variable data sets (EMD) were checked employing Kolmogorov-Smirnov test. For the investigation of influence of independent variable of gender (male and female) on dependent variable of EMD for each investigated muscle (LD and PD), paired t test was used. Δt LD - PD comparison was also conducted by using two sample-t test. With the purpose of ensuring no significant trial effect, the data blocks of the first and second measurement were investigated using paired t test.

RESULTS

The kayak performances lasting two 20 seconds intervals ensured 18 and 20 forward strokes for female and male subject, respectively. All the results were calculated using those stroke data for each subject. EMD by muscle group and subject is presented in Table 2 below.

TABLE 2: EMD values (mean ± SD) of the LD and PD for male and female subject.

Subjects	EMD		
	LD	**PD**	**Δt LD - PD**
Male	51,25±3,01	37,25±3,57	14±2,61
Female	61,13±2,94	49,37±4,43	11,75±4,46

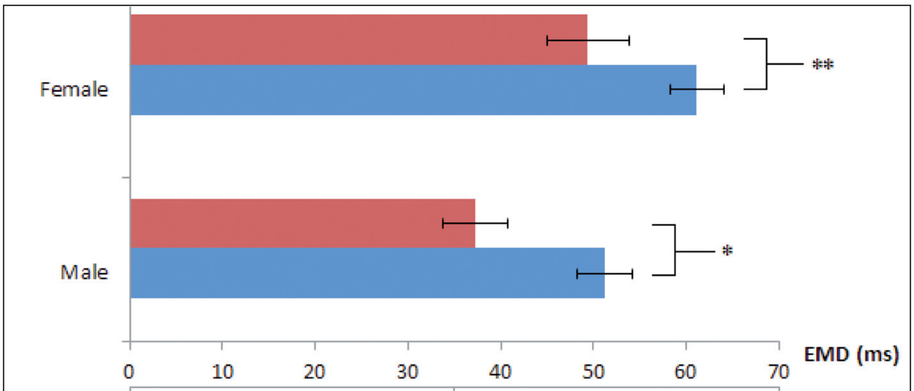
EMD: Electromechanical delay; LD: Latissimus dorsi; PD: Posterior deltoid.

There was no significant difference between data blocks of the first and second measurement for the male subject (LD, $p>0.7$; PD, $p>0.5$) and the female subject (LD, $p>0.9$; PD, $p>0.2$). For the data set of the both subjects, there was a significant difference between EMD of the LD and PD ($p<0.001$). The EMD comparison between male and female subject for both muscles investigated revealed statistically significant difference ($p<0.001$). The comparison graph by investigated muscles is displayed in Figure 3.

DISCUSSION

In the presented study, a 3-axis accelerometer and surface EMG were synchronized to detect EMD of investigated muscles (PD, LD) and inter muscular activation latency during dynamic flatwater kayaking stroke. EMG synchronized accelerometer allowed to detect the onset of the joint motion at the beginning of the catch phase following a short pause of recuperation phase. Here, EMG shows the exact firing of the muscle fibers whereas accelerometer displays the onset of mechanical movement in the given joint.

As it has been mentioned in findings section, the measured EMD values of the present study were repeatable for two consecutive measurements ($p>0.500$) and the results were between 37 ms and 61 ms among the investigated muscles and subjects. The results indicate that EMG-accelerometer based EMD assessment has taken part in spectrum of previously reported values in clinical studies. Those studies were investigating EMD under various voluntary contraction conditions and by using different EMD measurement methods which are generally complex or costly.[10-12] In their well-documented study, Begovic et al., employed force sen-



	Male	Female
🟥 PD	37,25	49,37
🟦 LD	51,25	61,13
Δt LD - PD	14	11,75

FIGURE 3: EMD values for the PD and LD muscles. *Statistically significant difference (p<.05) between LD and PD result in male subject. **Statistically significant difference (p<.05) between LD and PD result in female subject.

EMD: Electromechanical delay; LD: Latissimus dorsi; PD: Posterior deltoid.

sor - EMG couple to detect EMD under voluntary isometric contraction and found a delay of 49.7 ms.[2] Other results reported by researchers were 49.5-55.5 ms, 39.6 ms, 38.7 ms, 37.8-56.5 ms, 57.2 ms, 40-60 ms and 24-63 ms.[1,3.24-26,28] Some researchers, however, reported EMD times as low as 8.5 ms, 8 ms and 11.63 ms, using electrical stimulation technique for muscle trigger.[9,29,30] The time difference between these studies and present study may be explained by the fact that movement was elicited by electro stimulation in those studies.

Fiber type distribution and muscle-tendon stiffness are two substantial factor of EMD.[31] It was reported by number of researchers that women display longer EMD values than men.[24,25,32,33] The longer EMD values in females may be attributed to differences in muscle composition.[28] However, considering that fiber type composition of the LD is more fast twitch dominant than PD, the findings of the present study conflicts with these suggestions, as EMD of the LD was found to be longer than that of PD.[34] The reason of this latency may be resulting from longer conduction distance from LD electrode to joint than from PD electrode to joint. Because the mechanical response of the PD and LD was observed in the same joint, however the electrical onsets of the two were measured from distinct points. Considering the fact that kayak stroke is a learned complex motor pattern, coordinated PD and LD activation is expected in an elite kayak athlete. As a result, the present research suggested that recruitment order of motor units alters with distance to ensure a synchronized glenohumeral extension, which may be explained as acquired skill.

The activation order of the PD and LD at the beginning of the catch phase may be another reason of the latency between PD and LD electrical onset. Logan and Holt, carried out an in depth analysis of the forward flatwater kayak stroke in terms of the muscular activation patterns in each phase of the motion.[15] The researchers reported that, the catch phase is initiated by simultaneous downward shoulder girdle rotation and gleno-humeral joint extension. As a result, activation onset of the LD and PD might not be exactly simultaneous. This means that, the two may behave as synergists at the initiation of the motion, however, after a time of a few ten-milliseconds they might act as agonists of the motion. This phenomenon has been termed as motor variability, which is usually present even in the best-trained subjects.[35]

Shorter EMD might reflect a reduced delay in force transmission from the muscle tendon unit to joint. This could promote the performance of dynamic movements, as EMD is considered to reflect an important aspect of neuromuscular reaction time.[28,36] Considering the fact that stroke rate of Olympic flatwater kayak is between 80-120 strokes per minute, an improved EMD time of a few milliseconds may yield a result of up to a few hundred milliseconds in a race distance. This brings the question whether it is possible to reduce the EMD time. Some researchers reported that repetitive dynamic contractions can train the motor units to fire in synchrony, which may decrease the EMD time.[37-40] Kamen et al., found decreased delay times in power athletes compared with endurance athletes during a static measurement.[41] Linford et al., investigated effects of neuromuscular training on EMD and reaction time on peroneus longus muscle (n=36).[4] The researchers planned a 6 week neuromuscular training program. At the end of the program they measured the EMD of the peroneus longus muscle by a supramaximal percutaneous electric stimulus of the common peroneal nerve and resultant motion on force plate while on static stance. The EMD results displayed an increasing trend after 6 week period while reaction time decreased. This may be due to fact that the EMD was measured during stimulus elicited contraction on static stance as muscle spindle sensitivity changes may have been initiated by the movement patterns of the neuromuscular training. The EMD would likely be not longer if the contraction was voluntary, as the researchers suggested that spindle sensitivity and resultant muscle stiffness may be desensitized due to training during the stance. Kyrolainen and Komi and Komi found diminished tendon tap reflexes (in a static position) in 3 of 4 muscles of power versus endurance athletes.[5,42,43] Further study is needed to explain EMD responses to various training designs so that the effects of training on practical dynamic EMD may be employed in annual periodization.

Experimental designs to measure EMD of a muscle in isolated conditions may yield realistic results in those particular conditions. However, in forward kayak stroke, which displays both open and closed kinematic chain motion characteristics, EMD values may differ from those muscle or joint isolated measurement conditions. As a result, joint isolated EMD measurement experimental designs may, possibly, not give practical results to track EMD changes in dynamic forward kayak stroke motion. Employment of EMD measurement system proposed in present study would enable to determine EMD under dynamic kayak motion in both conditions: on ergometer and on water. As the present study was conducted to develop a new methodology, the researchers did not aim to study with a large sample size.

CONCLUSION

EMD time plays an important role in athletic performance. The present study aimed to develop an EMD measurement system based on integration of EMG and accelerometer. The main limitation of the study was limited number of the subjects. Hereby, measures of centrality and spread were calculated treating every kayak stroke as a sample. The results measured during dynamic forward kayak motion resided close to ones in literature. Application of the suggested system may render flexibility to determine EMD for various sports and under miscellaneous conditions such as: (1) multiangular/multiplanar complex motions, (2) during mobile and dynamic motions, (3) investigation of multiple muscles simultaneously which allows ensuring inter-muscular coordination comparison.

Acknowledgment

The authors would like to thank the participants involved in the study, for their eager involvement and patience.

Conflict of Interest

Authors declared no conflict of interest.

Financial Support

The present study is supported by Anadolu University Scientific Research Project Council (project number: 1704S098).

Authorship Contributions

***Idea/Concept:** Eren Kaya, İsmail Bayram, Ali Onur Cerrah, Hayri Ertan; **Design:** Eren Kaya, İsmail Bayram, Ali Onur Cerrah; **Data Collection:** Eren Kaya, İsmail Bayram; **Data Processing:** Eren Kaya; **Analysis and/or Interpretation:** Eren Kaya, İsmail Bayram, Ali Onur Cerrah, Hayri Ertan; **Literature Review:** Eren Kaya, Hayri Ertan; **Writing the Article:** Eren Kaya, Ali Onur Cerrah; **Review/Consultancy:** İsmail Bayram, Ali Onur Cerrah, Hayri Ertan.*

REFERENCES

1. Cavanagh PR, Komi PV. Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. Eur J Appl Physiol Occup Physiol 1979;42(3):159-63.
2. Begovic H, Zhou GQ, Li T, Wang Y, Zheng Y. Detection of the electromechanical delay and its components during voluntary isometric contraction of the quadriceps femoris muscle. Front Physiol 2014;5(494):1-8.
3. Howatson G, Glaister M, Brouner J, van Someren KA. The reliability of electromechanical delay and torque during isometric and concentric isokinetic contractions. J Electromyogr Kinesiol 2009;19(5): 975-9.
4. Linford CW, Hopkins JT, Schulthies SS, Freland B, Draper DO, Hunter I. Effects of neuromuscular training on the reaction time and electromechanical delay of the peroneus longus muscle. Arch Phys Med Rehabil 2006;87(3):395-401.
5. Blackburn JT, Bell DR, Norcross MF, Hudson JD, Engstrom LA. Comparison of hamstring neuromechanical properties between healty males and females and the influence of musculotendinous stiffness. J Electromyogr Kinesiol 2008;19(5): e362-9.
6. Chen HY, Chien CC, Wu SK, Liau JJ, Jan MH. Electromechanical delay of the vastus medialis obliquus and vastus lateralis in individuals with patellofemoral pain syndrome. J Orthop Sports Phys Ther 2012;42(9):791-6.
7. Yavuz SU, Sendemir-Urkmez A, Türker KS. Effect of gender, age, fatigue and contraction level on electromechanical delay. Clin Neurophysiol 2010;121(10):1700-6.
8. Howatson G. The impact of damaging exercise on electromechanical delay in biceps brachii. J Electromyogr Kinesiol 2010;20(3): 477-81.
9. Shultz SJ, Perrin DH. Using surface electromyography to assess sex differences in neuromuscular response characteristics. J Athl Train 1999;34(2):165-76.
10. Longo S, Cè E, Rampichini S, Devoto M, Venturelli M, Limonta E, et al. Correlation between stiffness and electromechanical delay components during muscle contraction and relaxation before and after static stretching. J Electromyogr Kinesiol 2017;(33):83-93.
11. Dieterich AV, Botter A, Vieira TM, Peolsson A, Petzke F, Davey P, et al. Spatial variation and inconsistency between estimates of onset of muscle activation from EMG and ultrasound. Sci Rep 2017;(7):42011.
12. Smith CM, Housh TJ, Hill EC, Johnson GO, Schmidt RJ. Dynamic versus isometric electromechanical delay in non-fatigued and fatigued muscle: A combined electromyographic, mechanomyographic, and force approach. J Electromyogr Kinesiol 2017;(33):34-8.
13. Plagenhoef S. Biomechanical analysis of Olympic flatwater kayaking and canoeing. Res Q 1979;50(3):443-59.
14. Fleming N, Donne B, Fletcher D, Mahony N. A biomechanical assessment of ergometer task specificity in elite flatwater kayakers. J Sports Sci Med 2012;11(1):16-25.
15. Logan SM, Holt LE. Sports performance series: The flatwater kayak stroke. National Strength & Conditioning Association Journal 1985;7(5):3-11.
16. Michael JS, Rooney KB, Smith RM. The dynamics of elite paddling on a kayak simulator. J Sports Sci 2012;1(8):1-8.
17. Jackson PS. Performance prediction for Olympic kayaks. J Sports Sci 1995;13(3):239-45.
18. Kendal SJ, Sanders RH. The technique of elite flatwater kayak paddlers using the wing paddle. International Journal of Sports Biomechanics 1992;8(3):233-50.
19. McDonnell LK, Hume PA, Nolte V. Place time consistency and stroke rates required for success in K1 200-m sprint kayaking elite competition. Int J Perform Anal Sport 2013;13(1): 38-50.
20. Gomes BB, Ramos NV, Conceição FAV, Sanders RH, Vaz MA, Vilas-Boas JP. Paddling Force Profiles at Different Stroke Rates in Elite Sprint Kayaking. J Appl Biomech 2015;31(4):258-63.
21. De Luca CJ. The use of surface electromyography in biomechanics. J Appl Biomech 1997;13(2):135-63.
22. Sprigings E, McNair P, Mawston G, Sumner D, Boocock M. A method for personalising the blade size for competitors in flat water kayaking. Sports Eng 2006;9(3):147-53.
23. Drapała J, Brzostowski K, Szpala A, Kucharska AR. Two stage EMG onset detection method. Arch Control Sci 2012;22(4):427-40.
24. Winter EM, Brookes FB. Electromechanical response times and muscle elasticity in men and women. Eur J Appl Physiol Occup Physiol 1991;63(2):124-8.
25. Zhou S, Lawson DL, Morrison WE, Fairweather I. Electromechanical delay in isometric muscle contractions evoked by voluntary, reflex and electrical stimulation. Eur J Appl Physiol Occup Physiol 1995;70(2):138-45.
26. Zhou S. Acute effect of repeated maximal isometric contraction on electromechanical delay of knee extensor muscle. J Electromyogr Kinesiol 1996;6(2):117-27.
27. Hug F, Lacourpaille L, Nordez A. Electromechanical delay measured during a voluntary contraction should be interpreted with caution. Muscle Nerve 2011;44(5):838-9.
28. De Ste Croix MB, ElNagar YO, Iga J, James D, Ayala F. Electromechanical delay of the hamstrings during eccentric muscle actions in males and females: Implications for non-contact ACL injuries. J Electromyogr Kinesiol 2015;25(6):901-6.
29. Grosset JF, Piscione J, Lambertz D, Pérot C. Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. Eur J Appl Physiol 2009;105(1):131-9.
30. Nordez A, Gallot T, Catheline S, Guével A, Cornu C, Hug F. Electromechanical delay revisited using very high frame rate ultrasound. J Appl Physiol (1985) 2009;106(6):1970-5.
31. Viitasalo JT, Komi PV. Interrelationships between electromyographic, mechanical, muscle structure and reflex time measurements in man. Acta Physiol Scand 1981;111(1):97-103.
32. Bell DG, Jacobs I. Electro-mechanical response times and rate of force development in males and females. Med Sci Sports Exerc 1986;18(1):31-6.
33. Costa PB, Ryan ED, Herda TJ, Walter AA, Hoge KM, Cramer JT. Acute effects of passive stretching on the electromechanical delay and evoked twitch properties: a gender comparison. J Appl Biomech 2012;28(6):645-54.
34. Srinivasan RC, Lungren MP, Langenderfer JA, Hughes RA. Fiber type composition and maximum shortening velocity of muscles crossing the human shoulder. Clin Anat 2007;20(2):144-9.
35. Latash ML. Patterns of Single-Joint Movements. Neurophysiological Basis of Movement. 1st ed. Champaign: Human Kinetics; 1998. p.88-96.
36. Minshull C, Gleeson N, Walters-Edwards M, Eston R, Rees D. Effects of acute fatigue on the volitional and magnetically-evoked electromechanical delay of the knee flexors in males and females. Eur J Appl Physiol 2011;100(4): 469-78.
37. Hayes RC. Supraspinal and spinal processes involved in the initiation of fast movements. In: Landers DM, Christina RW, eds. Psychology of Motor Behavior and Sport. 1st ed. Champaign: Human Kinetics; 1977. p.91-105.
38. Hayes RC. A theory of the mechanism of muscular strength development based upon EMG evidence of motor unit synchronization. In: Landry F, Orban WAR, eds. Biomechanics of Sports and Kinanthropometry. Miami: Symposium Specialists; 1978. p.69-77.
39. Moritani T, Shibata M. Premovement electromyographic silent period and α-motoneuron excitability. J Electromyogr Kinesiol 1994;4(1):27-36.
40. Gabriel DA, Boucher JP. Effects of repetitive dynamic contractions upon electromechanical delay. Eur J Appl Physiol Occup Physiol 1998;79(1):37-40.
41. Kamen G, Kroll W, Zigon ST. Exercise effects upon reflex time components in weight lifters and distance runners. Med Sci Sports Exerc 1981;13(3):198-204.
42. Kyröläinen H, Komi PV. Neuromuscular performance of lower limbs during voluntary and reflex activity in power-and endurance-trained athletes. Eur J Appl Physiol Occup Physiol 1994;69(3):233-9.
43. Komi PV. Training of muscle strength and power: interaction of neuromotoric, hypertrophic, and mechanical factors. Int J Sports Med 1986;7 Suppl 1:10-5.