Stereophotogrammetry measurement of kinematic target effect as speed accuracy benchmark indicator for kicking performance in martial arts

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Purpose: The development of a motion capture system leads to fast and accessible ways of precise testing of athletes and their motor abilities. The striking performance in martial arts and combat sports requires measuring velocity in the context of successful contact with the target. The aim of this study was to present the novel kinematic target effect coefficient and its possible use as a speed accuracy benchmark of performance based on the example of taekwon-do roundhouse and frontal kicks. *Methods*: The stereophotogrammetry motion capture setup consists of 10 infrared cameras (NIR Vicon MX-T40). Analysis includes 180 kicks (roundhouse and frontal kicks) performed by 15 adult participants on a master level in taekwon-do. The kinematic target effect comparison includes two targets – a training shield and a table tennis ball hanging from the ceiling. Markers were placed on the lower extremities of participants. Spatial-temporal variables were registered for both kicking legs, techniques, and target types. *Results*: Both roundhouse and frontal kicks revealed target and marker dependent differences during its execution. The kinematic target effect coefficient values differ for the specific marker and kick type. *Conclusion*: The wireless motion capture systems could be helpful in the training process and an athlete's evaluation before sports competitions.

Key words: motion capture, strike velocity, speed-accuracy trade-off, performance analysis

1. Introduction

Martial arts finally became treated as a sport and eventually became an Olympic games discipline, as in the case of taekwondo [9], [24]. That was one of the reasons why martial arts became a subject of research in the field of sport studies in fields such as biomechanics or sports physiology. Sports performance analysis includes a broad range of assessments relating to an athlete's performance [22], [27], [29]. The common type of performance analysis includes various tests on the flexibility of martial arts practitioners [4] and also lower body strength [2], [11] or aerobic endurance [23]. The objective measurements in those fields give solid predictions about the possible outcomes of individual performances.

Accuracy and precision in martial arts are both crucial. It is a binary situation, as a strike is successful or unsuccessful. Successful strike means hitting an object in certain contests type such as special techniques [25] or breaking boards [6]. In all cases, the aim of the martial arts practitioner is to maintain high accuracy together with a high maximal velocity of the strike. According to Fitts et al. [16], there is a strict relation between accuracy and speed. It requires certain excellence in the technique performance to perform both a fast and a precise strike. In such a case, the trade-off phenomena is maintained, however, the overall focus and energy consumption rises [10], so

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a simple trade-off formula cannot be used as an objective value for all athletes.

Wireless motion capture systems and fast data processing encourage researchers to analyse the strikes velocity toward different targets. Authors are mostly interested in the roundhouse kick and the frontal kick that are characterized by distinguishable patterns of linear and circular motions, which are common for most types of martial arts [20]. The obtained results are very precise and facilitate the measurement of movement patterns and the effectiveness of the performed technique by returning the velocity values of a strike, the time of execution, as well as the body segment positions through movements [7] or striking force [17], [18]. These kinds of variables are obtained during the motion capture of specific techniques. It enables the researchers to verify which movement pattern is more effective and extends knowledge about a specific technique of the martial arts under analysis [8]. Meanwhile, Wąsik et al. used similar methods to capture the difference between the velocity values of the strikes on different targets, which recently have been termed the kinematic target effect, which is defined as the differences in the kinematics of a striking technique depending on the target type or lack of a physical target [26], [27]. This is an example of the application value of biomechanical research which can be useful for trainers and practitioners to modify their ability to perform better.

The main premise of this study is based on the phenomena of the target kinematic effect and the differences between the maximal velocities while hitting different types of targets. When we connect this to the speed-accuracy trade-off mechanism, we assume that there will be some pattern in the differences of the maximal velocities proportion with specifically paired target types. We propose to name this variable as the kinematic target effect coefficient, which stands for the difference in the maximal velocity of the kick between various targets.

Assuming an accuracy of 100% successful hits to the targets, we hypothesize that there may be significant differences in the maximal velocities proportion for the pair of targets, which differ in the size and mass. Additionally, we hypothesize that there might be a decrease in maximal velocities for kicking to smaller targets accordingly to a principle of accuracy trade-off mechanisms.

The aim of this study is to present the novel kinematic target effect coefficient and its possible use as a speed accuracy benchmark of the execution of a kick based on the example of taekwon-do roundhouse and frontal kicks with the aid of stereophotogrammetry methods.

2. Materials and methods

2.1. Apparatus

The study was conducted in the Human Motion Lab by means of a stereophotogrammetry method with the use of 10 infrared cameras (NIR Vicon MX-T40). The system captures marker positions with an accuracy of up to 0.5 mm, which gives an estimation error of velocity of around 0.06 m/s. The captured space has an ellipsoidal roller shape with a height of 3 me-
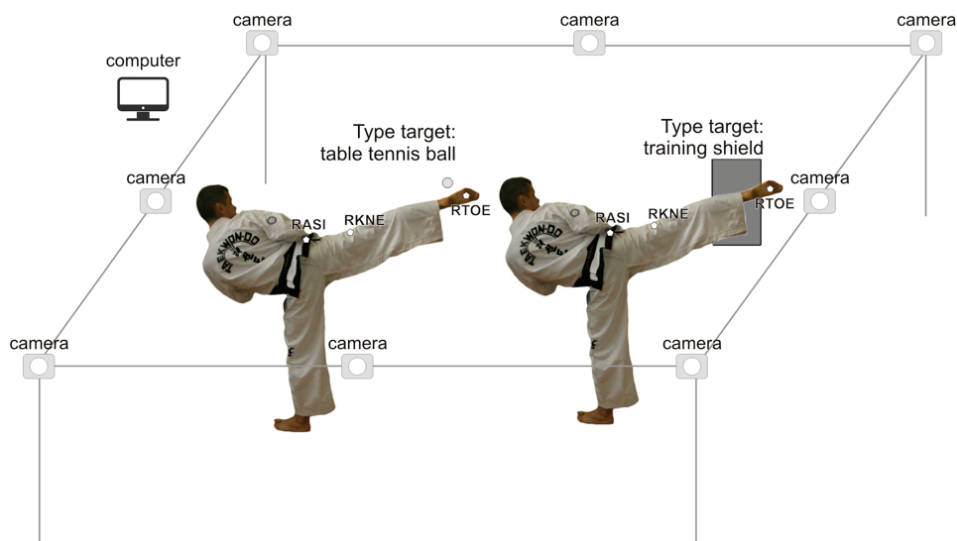

Fig. 1. Presentation of measurement setup with markers included in the analysis.
RASI – hip marker; RKNE – knee marker; RTOE – foot marker

tres and a base of 6.47 × 4.2 metres. The system captured movements of participants with a frequency of 370 frames per second with full resolution. The markers were placed on the dorsal part of the foot on the lateral side of the knee joint and on the hip (anterior superior iliac spine) (Fig. 1). The system registers three dimensional spatial-temporal data of marker displacement during the execution of the technique. We compute the resultant velocities based on the raw data stored in a c3d format. The maximal velocities were determined according to the Euclidean vector norm with the use of a specially dedicated library called pyomeca, which is a biomechanical library specially written for the python programming language (https://github.com/pyomeca) [14].

2.2. Procedures

The analysis includes 180 kicks performed by 15 male taekwon-do ITF (International Taekwon-do Federation) athletes (age: 22.5 ± 6.2 years; weight: 71.9 ± 11.5 kg; height: 175.7 ± 8.4 cm). Participants were expert-level athletes with a degree of 1st gup to 2nd dan, which signifies one grade below a master's degree and above. Their practice of taekwon-do has lasted for 4 years or more.

Participants performed two techniques from a sporting stance, which did not require strict foot placement in a similar manner as in sparring or competitions. There were two types of kick. The first one is the roundhouse kick, which is a circular type of kick with a throw-like pattern of movement. The second one is a frontal kick, which is linear with a push-like movement. The study of Kim et al. [13] shows that proximal parts of the body such as hip, reaches maximal velocity before more distal part such as knee. The most distal par of the body reaches the maximal velocity at the end of the movement, right before the contact with a target. In Figure 2, sample graph of resultant linear velocity in time on example of roundhouse kick for two type of target that were studied is presented. The contact area for roundhouse kick is a dorsal side of the foot up to an ankle joint, while for the frontal kick it is metatarsal-phalangeal joints area of plantar side of the foot. Both kicks were performed towards two types of targets – a training shield held by an assistant and a table tennis ball hanging from the ceiling on a string. Both kicks were performed on the high strike zone corresponding to the height of the opponent's head. The distance from the target was checked by the participants individually before the test, in order to equal the adjustment and to avoid height difference bias. There-

fore, both the distance and the height of a strike were normalized accordingly with regard to the size of the participant. Participants were informed that the motion capture begins and they should start when they feel ready. They were instructed to kick as fast and hard as they could. Each participant performs 3 kicks on the first target for each leg, then 3 kicks on the second target for each leg to avoid the fatigue effect. In total, 180 moves were captured (2 techniques × 2 legs × 3 times × 15 participants). The resultant linear velocities of markers were calculated using their positional changes relative to the *X*, *Y*, *Z* planes throughout each kick.
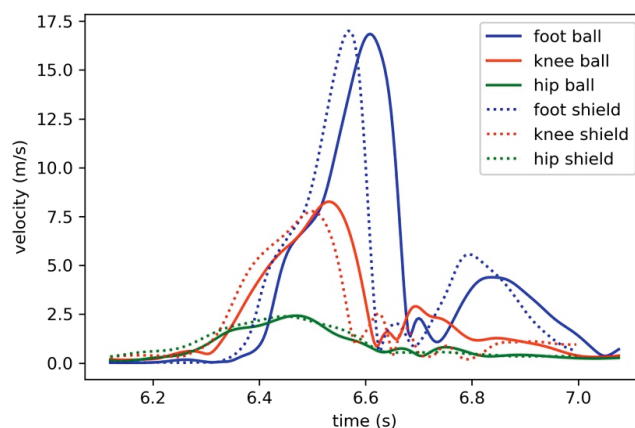

Fig. 2. Example of changes in resultant maximal velocity in time for roundhouse kicks towards two targets – table tennis ball and training shield. Foot, knee and hip refers to studied body segments

These values were used to compute the kinematic target effect coefficient (KTE), which informed the degree to which target type influenced the maximal velocities of martial artists hip, knee and foot during roundhouse and front kicks. The mathematical formula for calculating the coefficient was composed to establish values between 0 to 100. The coefficient is derived using two velocities obtained for the same marker in the same type of kick from a pair of analysed targets. For example, the first right roundhouse kick on a table tennis ball was compared to the first right roundhouse kick on a training shield. The lower of the two velocities was denoted as v_{min} and was divided by the higher velocity denoted as v_{max}.

$$KTE = 100 - \left(\frac{v_{min}}{v_{max}} \cdot 100 \right).$$

Theoretically, we can divide the relations between KTE coefficient values and the maximal velocities of

the strike on different targets into 4 circumstances: 1st – high mean maximal velocity of kicks and low KTE value (both fast and precise); 2nd – high mean maximal velocity of kicks and high KTE vale (fast, but lacks precision); 3rd – low mean maximal velocity of kicks and low KTE value (slow, but precise); 4rd – low mean maximal velocity of kick and high KTE value (slow and lacks precision) (Fig. 3). The theoretical concepts presented reflect the possible conditions of the participants and this division is meant to categorize their performance.
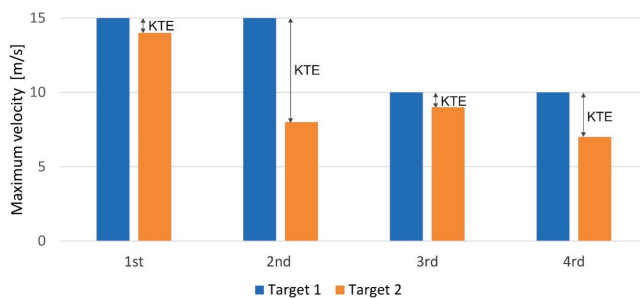

Fig. 3. Theoretical concept of general relation of the kinematic target effect coefficient values and maximal velocities. This relation refers to a single marker

2.3. Statistical analysis

The kinematic variables obtained were analysed by means of standard statistics computation methods like mean, median or standard deviation. Differences between the specific pairs of variables were verified by univariate (ANOVA) and multivariate (MANOVA) analysis of variance. The significance level was set for at least $p < 0.05$. When the significance level for specific computation is to be higher, we are to highlight with proper p value. To validate the existence of the 4 types of participants presented in Fig. 3, a cluster analysis set for 4 groups with 50 iterations for k-means method was used on a partial set of data. All computations were performed in Statistica 13 (TIBCO software inc.)

2.4. Ethics

All participants were informed about the procedures and signed a formal consent willingly to participate in the study. This study was conducted with the approval of the Bioethical Committee of University in Rzeszów, no. 2/6/2017, in accordance with the Helsinki Declaration.

3. Results

3.1. Motion capture results

In each of the analysed kicks on a specific target, there were higher mean and median values of maximal velocities while kicking the shield than kicking the table tennis ball, for all markers. Likewise, with the exception of the foot marker for a roundhouse kick, in other cases, the minimal registered value was lower for the ball target (5.70 m/s for the shield and 8.19 m/s for the ball), while the second exception was a higher maximal value of the foot marker than for a frontal kick on the ball (17.87 m/s) than the shield target (15.04 m/s). There was also a visible tendency towards higher standard deviation values for the distal marker and smaller values for the central one (hip) (Fig. 4).
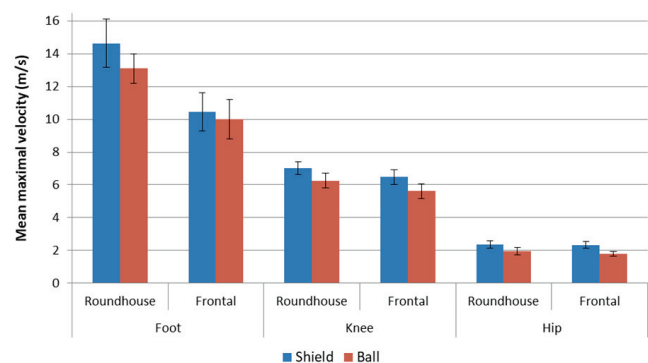

Fig. 4. Results of maximal velocities computation for all measuring circumstances

Separate analysis of the roundhouse kick performed by participants showed that there are significant differences between both the kicking side (right and left), targets (the tennis table ball and the shield) and markers (foot, knee and hip). Moreover, the joint effect between the kicking side and the target, as well as the marker and target were statistically significant. In the case of the frontal kick, the only statistically significant differences observed occurred between the targets and the markers without any joint effect. The multivariate analysis summarized with an additional categorical factor as a kick showed that for all separate categories, the results differ statistically, but for the joint effect, this only happened in the case of the marker and kick pair and joint effect of the kick, marker and target altogether (Table 1).

Table 1. Multivariate variance analysis of the maximal velocity values
in all tested cirumstances ($p < 0.01$ bolded)

Kick type	Effect	SS	MS	F	*p*
Roundhouse	side	**28.00**	**28.00**	**11.06**	**0.001**
	marker	**12557.09**	**6278.54**	**2480.53**	**0.000**
	target	**108.83**	**108.83**	**43.00**	**0.000**
	side*marker	8.13	4.06	1.61	0.202
	side*target	**13.45**	**13.45**	**5.32**	**0.022**
	marker*target	**30.57**	**15.28**	**6.04**	**0.003**
	side*marker*target	10.98	5.49	2.17	0.115
Frontal	side	5.93	5.93	3.24	0.072
	marker	**6010.90**	**3005.45**	**1640.76**	**0.000**
	target	**50.07**	**50.07**	27.34	**0.000**
	side*marker	0.24	0.12	0.06	0.938
	side*target	0.07	0.07	0.04	0.847
	marker*target	3.69	1.84	1.01	0.366
	side*marker*target	0.06	0.03	0.02	0.984
All kicks	side	**29.86**	**29.86**	**13.69**	**0.000**
	marker	**17908.86**	**8954.43**	**4104.84**	**0.000**
	target	**153.27**	**153.27**	**70.26**	**0.000**
	kick	**559.30**	**559.30**	**256.39**	**0.000**
	side*marker	4.33	2.16	0.99	0.371
	side*target	7.72	7.72	3.54	0.060
	marker*target	12.54	6.27	2.87	0.057
	side*kick	4.08	4.08	1.87	0.172
	marker*kick	**659.12**	**329.56**	**151.08**	**0.000**
	target*kick	5.63	5.63	2.58	0.108
	side*marker*target	5.43	2.71	1.24	0.289
	side*marker*kick	4.04	2.02	0.93	0.397
	side*target*kick	5.81	5.81	2.66	0.103
	marker*target*kick	**21.71**	**10.86**	**4.98**	**0.007**
	side*marker*target*kick	5.61	2.81	1.29	0.277

SS – sum of squares, MS – mean squares, F – Fisher's statistics.

3.2. Analysis of target kinematic effect coefficient

As in the descriptive statistics, the kinematic target effect coefficient values obtained for the pair of shield/ball targets is also higher for the roundhouse kick than for the frontal kick. The highest values of this coefficient were revealed for the hip marker (22.63 for the frontal kick and 19.63 for the roundhouse kick). The most approximate average values of the coefficient for both kicks were revealed for the knee marker, where both values were around 13.5 points. The highest differences in this coefficient value were observed for the foot marker (Fig. 5).

In the case of the multivariate variance analysis of the KTE, in separate cases of the two types of kicks as well as the combined types with a kick as a categorical variable, the only statistically significant differences were shown for the marker category, with one joint effect with the kicks together (marker and kick). The kicking side revealed no difference between the KTE values (Table 2).
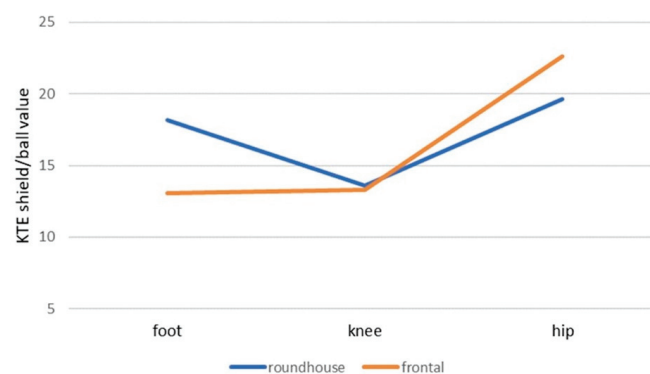

Fig. 5. Values of target kinematic effect coefficient for all measuring circumstances

Table 2. Multivariate variance analysis of the kinematic target effect (KTE) coefficient values
in all tested circumstances ($p < 0.01$ bolded)

Kick Type	Effect	SS	df	MS	F	p
Roundhouse kick	side	44.930	1.000	44.930	0.315	0.575
	marker	**1762.226**	**2.000**	**881.113**	**6.181**	**0.002**
	side*marker	169.099	2.000	84.550	0.593	0.553
Frontal kick	side	133.834	1.000	133.834	1.297	0.256
	marker	**5338.461**	**2.000**	**2669.230**	**25.870**	**0.000**
	side*marker	176.246	2.000	88.123	0.854	0.427
All kicks with joint effect	side	11.838	1.000	11.838	0.096	0.756
	marker	**5626.991**	**2.000**	**2813.496**	**22.899**	**0.000**
	kick	85.088	1.000	85.088	0.693	0.406
	side*marker	19.113	2.000	9.557	0.078	0.925
	side*kick	166.926	1.000	166.926	1.359	0.244
	marker*kick	**1473.695**	**2.000**	**736.848**	**5.997**	**0.003**
	side*marker*kick	326.232	2.000	163.116	1.328	0.266

SS – sum of squares, MS – mean squares, F – Fisher's statistics.

The cluster analysis results of the example of the right frontal kick have proven the construct validity of the model presented in Fig. 6. Participants are divided into 4 groups as a manner of the relation between the mean maximal velocity and the mean KTE values according to the description presented in the methods (Fig. 6).
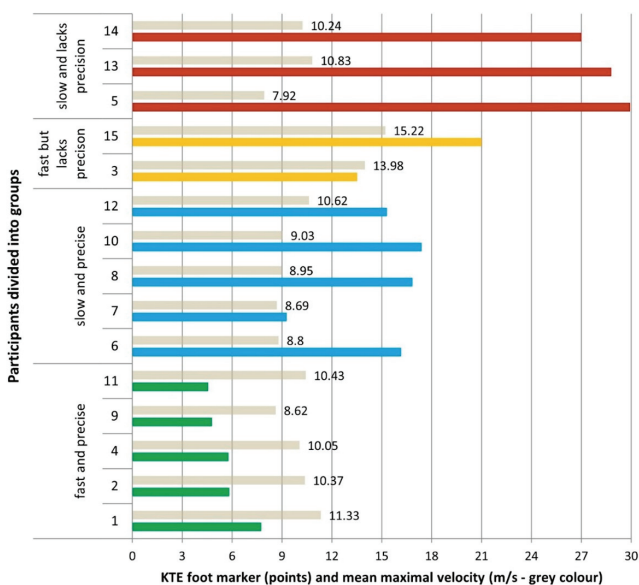

Fig. 6. Example of participant classification
based on the KTE value relation to the mean maximal velocities
of two targets for the right frontal kick

4. Discussion

The results of the maximal velocities presented are concurrent with the findings presented in other studies for a training shield, where the participants revealed the mean maximal velocity from 12.3 m/s [14], up to 15.65 m/s in the case of participants from other studies [1], [12]. The results of the frontal kick analysis could be compared to those of Abraham et al. [3], where participants obtained a mean velocity of around 11.77 m/s. A tennis table ball is not widely used as a target in martial arts biomechanical research, but our findings are comparable to the results for a training pad obtained by the participants of O'Sullivan et al. [19].

The statistical analysis revealed that during the execution of a roundhouse kick, there is a difference between the kicking sides, while this does not occur for a frontal kick, namely no lateralization has been observed. Perhaps this difference is related to the characteristics of both kicks. A roundhouse kick has a circular trajectory of a distant marker, while a frontal kick is linear [21]. In addition, there is difference in the area of the foot which makes contact with the target. In the case of a roundhouse kick, it is the dorsal site of the foot, while for a frontal kick, it is the plantar side that is limited to the area of the metatarsal-phalangeal joints. Therefore, the frontal kick is more demanding in terms of three-dimensional adjustments, especially for small targets, such as a table tennis ball.

For both of the kicks presented, there are significant differences for the markers. This enables us to assume that there is a necessity to observe the different body parts of the athletes to get a full scope of the technique and to identify any possible weaknesses in the kinematic chain of movement. The joint effect of the kick type category and markers allows us to conclude that each technique has its own characteristics in terms of body segment velocities and the relations

between them in a kinematic chain. Additionally, this movement pattern changes depending on the target type.

KTE also differed depending on the body part involved. The highest values, namely, the highest differences between the kick velocities on the analysed pair of targets were shown for the proximal part (hip marker). This could be explained by the analysis of the type of movement during the execution of the kick. The movement starts from the trunk muscles that move the pelvic girdle. The massive body parts accelerate like a flywheel at first, generating power that is later transmitted to the distal parts of the body that connects with the target. We can assume that prior to the execution of this movement, athletes subconsciously set the amount of torque that should be used depending on the target. Kicking a table tennis ball requires more spatial-temporal adjustments to hit the target successfully and requires greater control the limb after target contact to maintain balance. In contrast, the training shield is easier to hit and acts to absorb the energy of the kick much like a shock absorber, and, therefore, is less demanding in terms of maintaining balance.

KTE values differ for the techniques used and they are not a coefficient with a constant value for every kick presented by different participants. The different values for markers (foot, knee, and hip) allow us to conclude that KTE is a complex coefficient with many dependencies. Each of the kicks presented has its own unique profile not only for maximal velocities, but also for the KTE value.

There were no significant differences between the kicking side for KTE values. Despite the differences in the maximal velocities' values, the KTE value remains relatively similar. The target type has a general effect on the participant, without causing the lateralization effect to occur.

The kinematic target effect coefficient could find its place in the benchmarking of an athlete's performance in terms of the speed accuracy trade-off mechanism. A single test for the maximal velocity of the kick gives limited information about the precision abilities of martial arts exponents and provides no information about flexibility in the dynamic environment of a sports competition. Moreover, the trade-off mechanism presented by Fitts and his legacy successors cannot be simply implemented here. A basic understanding of this law suggests that the choice of one component comes at the expense of another. Nevertheless, the prediction of separate groups shows that there are athletes who kick both more quickly for both targets (group 1), and those who kick more slowly for

both targets. This fact validates the model where the trade-off mechanism is not a constant value phenomenon. The potential energy that could be divided in the case of these two aspects may differ between athletes. This may also suggest that different athletes need to undergo various training routines based on their profile from the KTE test results. This is concurrent with the trends in motor learning studies suggesting diverse learning at different stages of training [5]. Ultimately, an athlete who can maintain high velocity for both targets is more flexible to different environmental circumstances than an athlete who showed similar maximal velocity values with regard to a shield, but kicks much more slowly (high KTE value) with regard to a table tennis ball. This phenomena cannot be revealed until testing involves at least two different target types.

The limitation of this method lies in the complexity of the equipment necessary to obtain the maximal velocity values of the markers. However, accelerometers that are faster to set up have become more and more available on the market and more affordable, therefore, this method could become more popular in the near future. To further develop the basis of the coefficient presented, the relation with another pair of target types and techniques could be studied in the future.

In summary, the differences in the maximal velocities of kicks on two target types have proven the existence of the target impact on the technique performance. Both roundhouse and frontal kicks revealed the target and marker variable differences during their execution. The kinematic target effect coefficient differs for a specific marker and kick type, but contrary to the maximal velocity values, there is no observed lateralization, which means that the KTE values are not side-dependent. The kinematic target effect coefficient provides additional data about an athlete's accuracy abilities and flexibility. This indicator facilitates the monitoring of changes of the maximal velocity of the technique performed depending on the target type. Maintaining a similarly high velocity while hitting a precision-demanding target compared to a larger target that is easy to hit (low KTE values) indicates a professional level of expertise. However, the zero value of KTE is only hypothesized ideal, and price of precision needs to be paid in a certain degree in a lower velocity. This indicator could be helpful in the training process and the evaluation of athletes before sports competitions, especially the data for all three markers, where velocities of proximal part of the body could led to identifying the possible reasons of foot velocity variability.

5. Conclusions

The differences in the maximal velocities of kicks on two target types have proven the existence of the target impact on the technique performance. Participants obtained higher maximal velocities with a roundhouse kick while hitting a training shield (the mean values from 13.88 to 15.39 m/s) than in the case of a table tennis ball (the mean values from 13.06 to 13.13 m/s). The frontal kick performed by participants also had higher mean maximal velocities in the case of a training shield (10.34 to 10.57 m/s) than a table tennis ball (9.92 to 10.10 m/s). MANOVA analysis revealed target and marker variable differences ($p < 0.01$) for both roundhouse and frontal kicks during their execution.

The kinematic target effect coefficient differs for a specific marker and kick type. The highest mean values were revealed for a hip marker for the frontal kick (the mean value of 22.62 points), while the lowest for a knee marker while performing a roundhouse kick (13.62 points). Contrary to the maximal velocity values, there is no lateralization observed, which means the KTE values are not side-dependent.

A cluster analysis of a participant's performance justifies the use of the stereo-photogrammetry method of motion capture and kinematic target effect coefficient computation as a sufficient tool that gives additional data about an athlete's accuracy abilities. This indicator facilitates monitoring changes of the maximal velocity of the technique performed depending on the target type. Professional level of expertise could be expressed by similar velocity for both targets, resulting in low KTE value. This system could be helpful in the training process and the evaluation of athletes before sports competitions.

Acknowledgements

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