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KINEMATIC AND TEMPORAL PARAMETERS IN DIFFERENT MODALITIES OF THE REVERSE PUNCH MEASURED BY *IMU* SENSORS

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УНИВЕРЗИТЕТ У БЕОГРАДУ

ФАКУЛТЕТ СПОРТА И ФИЗИЧКОГ ВАСПИТАЊА

Весна Б. Вуковић

КИНЕМАТИЧКИ И ВРЕМЕНСКИ ПОКАЗАТЕЉИ УДАРЦА ГЈАКУ ЗУКИ У РАЗЛИЧИТИМ МОДАЛИТЕТИМА ИЗВОЂЕЊА МЕРЕНИ *IMU* СЕНЗОРИМА

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All studies have been conducted in accordance with the ethical guidelines outlined in the Declaration of Helsinki and received approval from the Ethics Research Committee of the University of Belgrade Faculty of Sport and Physical Education (02 No. 484-2).

Dedication

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Kinematic and temporal parameters in different modalities of the reverse punch measured by IMU sensors

Resume

Being able to perform the point-worth technique is a determining factor in distinguishing between winning the championship title and experiencing failure. For that reason, elite karate athletes are continually faced with the imperative to enhance their scoring abilities in dynamic combat environments. To improve technique, it is necessary to adopt a novel methodological approach based on investigation in realistic surroundings. Stepping out of the usual laboratory setting thus demands combining a set of specific tests with a reliable measurement device.

These requirements determined the aim of the research, which was to analyse the technical aspects of the reverse punch aimed at the body. The technique qualities, i.e., kinematic and temporal indicators of the punch in different modalities, were assessed by using wireless technology in surroundings that replicated training and competition environments. The results of the research are presented in three published studies addressing the main points of such an approach.

The findings of the first study presented in this dissertation confirmed that IMU sensor technology is valid and discriminatory with the respect to the specific indicators of the reverse punch and within different modalities of performance. The results of the second study revealed that the timeline of kinematic indicators in the developmental phase of the reverse punch may be used as predictors of the punch efficiency. In addition, the data collected from the hand indicates a tendency to exhibit higher degrees of stability when compared to the body. The study also proposed ten karate-specific tests with insightful placement of wireless devices on the most informative points of the body within a multimodal experimental set-up. The third study questioned if the impact is influenced by the conditions of execution and revealed the difference in the temporal and kinematic variables of the reverse punch between the applied modalities. Significant correlation coefficients were observed between the variables pertaining to body and hand measurements, with both large and medium correlation coefficients.

Overall, this research made a contribution to understanding the kinematic and temporal punch patterns in the developmental phase of RP in different modalities of execution as a foundation for individual approaches to enhancing punch efficiency. Apart from that, a novel, simple, and easy-to-use method for technique analysis was proposed. The main advantage of this method is its in-field use, i.e., during realistic combat tasks in a common fighting environment. Finally, such an approach can be used to improve the training and competitive practice of elite-level karate athletes by identifying the potentially weak points in their RP execution.

Keywords: *gyako tsuki*; standardised testing; elite athletes; kinematic sensors; technique analysis; acceleration; velocity; rotation angle; timeline

Scientific field: Physical education and Sport
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Кинематички и временски показатељи ударца гјаку зуки у различитим модалитетима извођења мерени IMU сензорима

Резиме

Фактор који прави разлику између освајања шампионске титуле и пораза је способност да се изведе техника вредна поена. Из тог разлога, елитни каратисти су константно суочени са захтевом да у динамичном борбеном окружењу подижу своје тхеничке способности на виши ниво. Унапређење технике захтева усвајање новог методолошког приступа заснованог на истраживању у реалистичном окружењу. Стога, отклон од уобичајеног лабораторијског приступа захтева комбиновање скупа специфичних тестова и употребу поузданих мерних уређаја.

Ови захтеви су одредили циљ истраживања, тј. анализу техничких аспеката ударца *гјаку зуки* усмереног на тело. Технички аспекти ударца, односно кинематички и временски показатељи у различитим модалитетима извођења, процењени су коришћењем бежичне технологије у окружењу сличном условима тренинга и такмичења. Резултати истраживања представљени су у три публиковане студије које се баве главним аспектима овог приступа.

Налази прве студије представљене у овој дисертацији потврдили су да је IMU (Internal Measurement Units) сензорска технологија валидна и дискриминаторна у погледу специфичних индикатора ударца *гјаку зуки* и у оквиру различитих модалитета перформанси. Резултати друге студије су открили да се временска линија кинематичких показатеља у фази развоја ударца *гјаку зуки* може користити као предиктор ефикасности технике. Поред тога, подаци прикупљени са шаке указују на тенденцију испољавања вишег степена стабилности у поређењу са оним који потичу са тела. У студији је, такође, предложено десет тестова специфичних за карате, у комбинацији са постављањем бежичних уређаја на најинформативније тачке тела, и то у оквиру мултимодалне експерименталне поставке. Трећа студија довела је у питање услова извођења на завршницу ударца, а утврђена је разлика у временским и кинематичким варијаблама ударца *гјаку зуки* између модалитета извођења. Утврђена је значајна повезаност варијабли (тела и шаке), са високим и средњим коефицијентом корелације.

Сумарно, ово истраживање доприноси разумевању кинематичких и временских параметара у развојној фази ударца *гјаку зуки* у различитим модалитетима извођења као основе за индивидуални приступ у повећању ефикасности технике. Поред тога, предложен је нов, једноставан и за употребу лак методолошки приступ у анализи технике. Његова главна предност лежи у могућности употребе ван лабораторијских услова, односно у реалистичним борбеним задацима и уобичајеном борбеном окружењу. Најзад, такав приступ може побољшати тренажну и такмичарску праксе елитних каратиста и то путем идентификације потенцијалних слабости приликом извођења ударца *гјаку зуки*.

Кључне речи: *гјаку зуки*; стандардизовано тестирање; елитни спортисти; кинематички сензори; анализа технике; убрзање; брзина; угао ротације; временска линија

Научна област: Физичко васпитање и спорт
Ужа научна област: Науке физичког васпитања, спорта и рекреације
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1. Introduction

An enhancement of sports skills is probably one of the most important requests in the carreer of an athlete,[1,2] irrespective of the level of competition.[3] The aim of the training is what changes.[2] Shifting the training focus in some combat sports is possible on account of fundamental knowledge of punches.[4] For that reason, the reverse punch (RP) aimed at the body (in Japanese, *gyako tsuki chudan*) is perhaps the most studied karate technique. Yet, its core kinematic elements still seem to provoke undiminished research interest.

The majority of combat sports are recognised through punching techniques.[4] Although karate has much in common with various combat sports, its core concept as a martial art sets it apart. Karate technique is built around the idea of doing as much permanent damage as possible to an opponent. To be able to produce such harm with only one strike, the karate practitioner needs to have reached a very high degree of expertise. The very same intention must be demonstrated in sports fighting, but with one crucial modification: control over the delivered technique. In sports karate, control is defined as the ability to perform a technique according to the highest standards without injuring the opponent. Being in a score advance is possible on account of the criteria of efficiency. No such outcome can be expected without a stable stance as support for a point-worth technique.[5] Stance stability is achieved on account of lengthening. Such stance results in a centre of gravity closer to the ground. In addition, the scoring technique is characterised by explosive performance. In short, achieving maximum efficiency requires optimal engagement of psychophysical capacities, effort, attention, and energy. However, the particular demand is everything but simple to reach. The dynamics of sports fights demand a swift movement in the fighting area, fast reactions, and adaptation to the conditions of the fight while loading the maximum possible body mass into the distal segment of the kinetic chain, i.e., the fist. Understanding such a multi-layered process, which consists of demanding and simultaneous actions, is not possible without kinematic analysis.

The researchers have mainly been trying to address this issue under strictly controlled conditions with equipment that necessitates expertise in application. The complexity of the human systems that act in synergy[6] led the researchers to combine diverse measurement apparatuses, such as marker-based optical systems and force platforms, or electromyography.[5,7–11] But the extensive logistics and research funds are still the problem. Apart from that, the biggest issue is the results gained under controlled conditions in laboratory settings. Numerous studies have highlighted the need for measurements in an environment that is compatible with reality, whether it is training or competition.[12,13] Wearable sensor technology might be the solution. Recently, these devices have become widely used in numerous research projects. Ergonomic as they are, they provide testing in actual circumstances and deal with the most diverse issues in connection with human movement, regardless of whether it is elite sport, recreation, or therapy.[14–16] The main point is that the sensors do not affect the movement while at the same time providing relevant data about the monitored phenomenon.[17] Despite the possibilities they provide, wireless kinematic sensors have not yet become an integral part of combat sports research.[18]

2. Theoretical Approach

Karate was publicly introduced in 1922 by Funakoshi Gichin.[19] On a one-century development path, karate has transformed. Although the essence of traditional martial art is maintained in a persistent fighting orientation, contemporary karate has evolved into a complex sport divided into two distinguished disciplines: *kata* and *kumite*.[20]

RP is a cornerstone in both *kata* and *kumite* practice;[19] what differs are standards of efficiency. *Kata* is a predetermined sequences of actions that constitute offence and defence activity formally organised and performed in unity.[20] Thus, the technique must demonstrate a high level of strength and stability, along with speed in transition and a sharp ending that emphasises its power.[11] In contrast, no such predictability or prearranged series of techniques is common for *kumite* – sports combat.[21] Although each discipline has its own requirements,[21] the basis of the punch execution remains constant.[19]

2.1 The Fundamentals of Karate Technique

In karate, basic technique training employing all conventional principles of martial art[22] is founded on a large number of repetitions at various speeds of execution (from very slow, controlled, and with an active mind set to details to the fastest possible and automated performance).[19] From a traditional point of view, karate training takes place in several stages.[23] It is characterised by gradual mastery of the technique curriculum, which includes stances, transitional movements, punches, kicks, blocks, and swiping technique.[24]

Regardless of the practiced discipline, several points are regarded as of primary importance in learning karate technique and therefore to the reverse punch. These points also represent the fundamentals of competition rules in technique assessment.[25] Nakayama[19] especially emphasises:

(1) *Form, Balance, and Centre of Gravity*: In order to kick or punch with success, the body as a whole must work harmoniously and provide the required stability. But the centre of gravity is constantly changing, meaning that dynamic stability ensures efficiency.

(2) *Power and Speed:* Concentrating maximum power at the moment of impact is the ultimate goal. Speed, allowing good punching or kicking control, is an important element in power application. The final outcome must be moving with maximum speed and executing technique with full control.

(3) *Concentration of Power:* This principle summarises the requirement that the technique be performed in a manner that requires application of all body parts simultaneously, in contrast to execution with punching the arm alone, for example.

(4) *Muscular Power:* Engagement of the proper muscle groups and timed muscle contraction.

(5) *Rhythm*: Although rhythm is an important element in both *kata* and *kumite* practice, it is especially emphasised in *kata* performances. Nakayama (1989) emphasises strength, speed, and smooth transition as the three essential components of *kata* performance. Strength is worth it only if it's applied at the correct time. Speed by itself has no value if it is not controlled. The two types of speed are recognised as important: fast execution of a single technique as well as fast interconnection of several techniques.[19]

(6) *Timing*: Good timing is considered to be the delivery of technique at the point when it has the greatest potential and will likely jeopardise the opponent at the highest level.

(7) *Lower Abdomen and Hips*: The importance of the lower abdomen in Japan is summarised in the concept of the *tanden*, which is recognised as a central area of human energy in the region behind the navel. If the practitioner takes the correct stance, the centre of gravity will be found in the same spot. When tanden's strength is concentrated in performing karate techniques, the pelvis and hipbone are firmly supported by the thighs, and the torso is strongly supported by the spine. This kind of support between the body segments creates a powerful technique.[19]

These fundamentals are implemented in karate practice from the very beginning. *choko tsuki* (ChT) is typically the first technique taught to students who are just starting out karate practise. ChT is a form of the RP practiced in a natural, standing stance (in Japanese, *shizentai*). The main goal of such practice is to teach the novices to be concentrated on details, such as timely integrating the actions of one's limbs, directing the punch properly without redundant deviations from the line of performance, and timing muscle contractions. In the next phase, practitioners focus on the regulation of hip movement. Traditionally, it is achieved through a variety of tasks performed in the basic stance, which is *zenkotsu dachi*.[19] After this point *kata* and *kumite* competitors differentiate in more specific way. Although it is relatively uncommon to engage in solo training,[22] a significant emphasis in combat karate is placed on practising against an opponent, whether utilising supplementary equipment or not, while assuming a combat stance.

2.2 Specific Requirements of *Kumite* Practice

In contrast to *kata*, which can be considered a closed skill distinguished by the absence of the opponent, *kumite* is an open-skill sport, meaning that modifications in combat settings are constant.[11] Competitors fight in five weight divisions. Karate combat lasts three minutes for both males and females,[25] and it is characterised by a high level of dynamism.[26,27] The majority of karate *kumite* is characterised by aerobic activity, constituting 77.8% of overall energy sources. The rest of the fight profile is composed of anaerobic alactic and lactic sources of energy.[28] In order to gain an advantage over the opponent, fighters must efficiently deal with number of concurrent information and modify their strategies in accordance.[29] Inconsistency of the combat conditions can also be recognised in the high level of fighting intensity followed by the high speed of various actions aimed at the opponent.[13] Nonetheless, the distance between the opponents is constantly changing, demanding the athletes permanently rearrange tactics and shift between offence, defence, or counter-attack. In compare to lower limb technique, punches are more frequent. This applies regardless of the type of action.[27] They are also faster in compare to kicking techniques.[13] The successive inclusion of segments of the kinetic chain (both lower and upper extremities) in the punching technique indicates a possible range of inconsistencies in execution.[4,13]

Scorning is not an easy task. The technique performed has to be up to par with regard to quality. That always means the highest level of energy and speed, along with optimal timing.[30] Special attention is paid to controlled power, as exceeding it can lead to penalising the offender[25] and altering the outcome of the match. The ultimate goal is to exceed the rival through more effective technique. Thus, the final objective is to design strategies for successful training, highlightening the critical factors of technique efficiency and control.

2.3 Technical Quality Indicators

Analysis of the combat activity at the World and European championships showed that elite fighters mostly gain an advantage using RP. Also, they prefer scoring the body in comparison to the head.[27] RP is characterised by its constantly growing acceleration. Within the first phase of the punch, hand speed rises to 12.5 m/s.[12] RP is performed in a *fudo dachi* (combat) stance. The hand delivering the technique is on the contralateral side of the leg that is leading. As such, RP can be broken down into phases. At each stage, features emerge that indicate a general pattern of performance. The punch has a kinetic chain that is structured in a sequential manner. The lower part of the chain, consisting of leg joints, is the initiator of the movement. The very first activity is associated with the rare leg ankle. Knee and hip joints are following. The body rotates, and the upper, ipsilateral part of the chain takes the lead. The shoulder, elbow, and wrist are involved in the movement in this order. Such structure, along with the specifics of the human locomotion subsystems[6] makes the RP complex motion from the perspective of degrees of freedom.[31]

Punching effectively is, therefore, difficult to achieve. Many components of human motor control must be adjusted in a number of ways.[6] Linear as well as rotational quantities help with understanding the mechanics of the movement, differentiation between types of punches,[12,32] and skill evaluation.[33] When it comes to the reverse punch, the energy and power that are conveyed to the opponent are directly proportional to the velocity with which the punch is delivered.[13] Thus, acceleration and velocity[13,34] are key elements of the punch’s kinematic pattern. In addition, the timing of the incorporation of different body parts into the movement's sequential structure has an effect on the punching speed as well.[35,36] Taking into consideration the role that the lower part of the kinetic chain plays in the delivery of the punch,[4] the angular speed of the pelvis should also be taken into account.

2.4 Previous Research

Diverse aspects of the reverse punch have been investigated under numerous performance conditions and methodological approaches.

Analysing the reverse punch of four males with different combat backgrounds, Stull and Barham revealed differences in the obtained kinematics. Compared to the rest of the participants, the *Shotokan* karate athlete achieved the highest value of hip velocity and the greatest horizontal hip displacement. In addition to this, peak hip, shoulder, and wrist velocities occurred earlier in the timeline, and the average wrist velocity was the highest. The main characteristics of the reverse punch performed by the karate athlete were: a peak hip velocity of 1.55 m/s at 42% of the total movement time; a peak shoulder velocity of 3.21 m/s at 53% of the total movement time; and a peak wrist velocity of 8.58 m/s at 80% of the total movement time.[37]

Chiu and Shiang investigated reaction time, attacking speed, and punch force in elite male and female karate athletes under four different conditions regarding standing positions. They revealed no systematic differences between straight and reverse punches. In relation to the reaction times, forward punch (550–650 ms) needed longer than stand punch (350–450 ms); and the attacking speeds in forward punch (2.7–3.0 m/s) were faster than stand punch (1.9–2.1 m/s). Investigators revealed that the punch motion time and total time of execution were related to the attacking distance. Furthermore, distance adjustment is associated with the experience and punch style of participants. As for the sex differences, female subjects achieved higher motion speeds in stand reverse punches.[38]

In addition to the study of the effect of stance on attack-time during a karate movement, Wang and Liu studied reverse punch under two stance conditions with 24 elite karate competitors. They concluded that, apart from the slight difference in punch speed, it was not significant. But, regarding attack time, combat stance influences the optimisation of performance.[39]

Dworak et al. studied velocity and kinetic parameters in punches and kicks performed by Shotokan competitors in laboratory settings. The main findings were: punches seem to be approximately two times weaker than kicks; regardless of being expected to be direct perpendicularly, there is a tendency for deviation of resultant force in *gyako tsuki*; punch velocity was calculated at the level of about 10 m/s, but the highest value was reached at 12.4 m/s; punch velocity is higher than kick velocity.[9]

Analysing five karate athletes with different levels of performance Emmermacher et al. concluded that acceleration is under the influence of individual characteristics in the "pushing phase" of punch execution. They also found that techniques with the shortest pushing times had relatively long decelerations.[40]

Girodet et al. used a 12-segment marker model in the kinematic and dynamic analysis of straight punches. They found that the peak force (1745 N) was reached 5 ms after the initial contact with the makiwara.[41]

Gulledge and Dapena compared mechanical factors in the reverse and three-inch power punches performed on a padded target. The smaller velocities immediately before impact were evidenced for the power punch (0.14 m/s) than the reverse punch (0.31 m/s), for the whole-body centre of mass; for the arm centre of mass (2.86 m/s vs. 4.68 m/s); and for the knuckle (4.09 m/s vs. 6.43 m/s). Also, the participants achieved a higher peak force when performing the reverse punch (1450 N) compared to the power punch (790 N). Nevertheless, the linear impulse of the fist in the first 0.20 s during the contact was slightly larger in the power punch than in the reverse punch (43.2 N·s vs. 37.7 N·s).[42]

Suwarganda et al. investigated if the sequence of the reverse punch under different conditions may have an impact on kinematic parameters such as punch time, distance, and joint velocities in nine elite karate athletes. On the basis of the linear resultant joint velocities of the shoulder and elbow, they identified two clusters: (1) more simultaneous movement sequence (mostly associated with female performances – 87%), and (2) more sequential movement sequence (mostly associated with male performances – 83%). It was also found that males achieve longer punch distances and higher peak linear resultant joint velocities for the shoulder, elbow, and wrist. In addition to this, both male and female participants seem to optimise their performance in terms of punch distance and peak linear resultant joint velocities, regardless of whether the punch was performed aiming at the body or the head.[43]

Cesari and Bertucco tested different ways of punch execution, comparing expert and novice performances. It was evidenced that karate experts tend to: use specific strategies to maintain body stability; reach higher upper limb velocity, punch impulse, and have a larger box displacement.[5] Kinematics analysis of karate techniques by a digital movie camera showed that *gyako tsuki* is a uniformly accelerated motion. The observed acceleration was about 63 m/s^2, and the highest obtained velocity was about 13 m/s.[44] It was also determined that the maximum acceleration of the wrist during a reverse punch differs when the punch is executed with (12.297 m/s^2) or without (21.252 m/s^2) impact on the target. In addition to that, in the first case, mechanical power might increase up to 8.21%, while in the case of hitting the impact, mechanical power increases up to 25.23%.[45]

Ionete et al. confirmed the sequential structure of the reverse punch. It was found that the technique starts with hip movement and reaches its end when the arm is fully extended in about 0.492 s. The highest obtained hip velocity was 0.912 m/s at 42% of total movement time; the peak shoulder velocity was 1.700 m/s at 65% of total movement time; and the peak wrist velocity was 5.125 m/s at 73% movement time.[46]

Vences Brito et al. compared the kinematic and electromyographic patterns of the *choku tsuki* punch between a group of experienced karate athletes and participants without karate backgrounds. They found that punch activity occurs within 400 ms, has near-distal end, and the intensity of activation is greater with the arm muscles compared to the forearm. As part of that, experience plays a great role in technical skill, meaning that karate athletes execute the punch with smaller amplitudes (the arm – flexion and internal rotation; the forearm – extension and pronation).[7]

In the extensive research Koropanovski compared characteristics of neuromuscular function in senior male national karate team, *kata,* and *kumite* competitors. The kinematic and dynamic characteristics of the *gyako tsuki* punch performed in different modalities (in the air or on the platform; with or without withdrawing the punching fist to the starting position; with or without stance elongation) revealed performance differences between athletes of different specialisations. Among others, registered differences were in relation to punch timeline. In a comprehensive analysis, it has been observed that *kata* competitors initiate their movements earlier than *kumite* competitors, irrespective of the performance conditions. This observation holds true for various reference points, such as the elbow and fist of the punching arm, the knee of the rear leg, and the ankle of the front leg. Specifically, kata competitors commence their hand movements at approximately 30% of the total timeline, whereas *kumite* competitors initiate their hand movements at around 40% of the overall movement time. When it comes to the velocity and acceleration of the analysed points, as well as the angular speed and acceleration of the elbow and knee, *kumite* athletes (in almost all conditions) achieve a statistically significantly higher maximum velocity of the fist in comparison to kata competitors. The same applies for the knee and ankle of the front leg while executing a reverse punch with stance elongation. On the contrary, *kata* competitors reached higher velocity and acceleration of the hip, as well as angular velocity and acceleration of the elbow and knee. Unexpectedly, analysis revealed more disruptions in the punch trajectory with *kata* athletes. As the final outcome of such differences, it was concluded that *kata* specialisation leads to movement predominantly based on a simultaneous kinematic scheme, while *kumite* orientation is characterised by successive kinematic schemes.[11]

Using 3D accelerometry in a Virtual Instrumentation System (VIS), Urbinati et al. measured the velocity of the *gyako tsuki*. The tested athletes performed the punch in the velocity range of 6 to 6.8 m/s, but maximum values varied between 10 and 10.2 m/s.[47]

Loturco et al. studied the relationship between punching acceleration and strength and power variables. The professional karate athletes, male and female, participated in the study where acceleration of the reverse punch was assessed in four different conditions aiming for different goals: (1) fixed distance (aiming for maximum speed); (2) fixed distance (aiming for maximum impact); (3) self-selected distance (aiming for maximum speed); (4) self-selected distance (aiming for maximum impact). The main findings were: males in comparison to females achieve higher acceleration values; different conditions and goal orientation influence punch acceleration (executing punch from a self-selected distance aiming for maximum impact produces higher accelerations in comparison to speed-oriented goals and fixed distances); lower values of acceleration are obtained aiming for maximum speed from a fixed distance than from a self-selected distance; and maximal strength and power of the upper- and lower-body are positively correlated to punch acceleration in the different conditions.[13] The influence of distance on the effectiveness of the punch is also evidenced in other combat sports.[48] In addition to punch kinetics, it was evidenced that the type of stance affects the punch impact force. In other words, a stance involving a larger number of segments (and therefore greater effective mass) generates more impact force.[49]

Martinez de Quel and Bennett compared a group of karate athletes to a group without karate experience to determine if expert knowledge and practice influence the execution time of movement performed under two conditions: 1) as a reaction, and 2) as self-initiated. On the basis of the kinematic analysis, the investigators concluded that a shorter time to peak velocity and movement time, as well as greater accuracy of the movement, are achieved in reactive than self-initiated movements. Even dough karate athletes reached higher peak velocity; determined differences were not under the influence of the skill level. Also, the study revealed no effect of the different types of auditory cues on reaction time or kinematics.[50] Different findings were reported by Mudrić et al. They conducted the study with the aim of evaluating a novel video-based method for testing reaction time (RT) in combat karate. Elite karate practitioners consistently obtained shorter simple and choice reaction time than the beginners regardless of stimulus.[51]

Fusch et al. aimed to identify and discriminate between two concepts of punch execution: consecutive and simultaneous sequences of motion. Motion capture with 61 reflective markers and eight Vicon cameras was used, and five experienced karate athletes participated in the study. The main finding confirmed proximal-to-distal sequencing of maximal joint velocities in both concepts. In addition to this, differences between concepts occurred in the range of motion; timing, maximal angular velocities, fist velocity at contact, execution time, distance, and horizontal shift of the centre of mass. They concluded that the main characteristics distinguishing two concepts are: (1) high pelvis momentum and backswing of the shoulder and elbow (in the case of a consecutive sequence of motion); and (2) shoulder involvement in the punch (in the case of a simultaneous sequence of motion).[52]

In order to assess wearable system application in combat sports, Saponara measured the kinematics of the reverse punch. Descriptive indicators showed that during punch performance, speed is almost uniformly growing up to 12.5 m/s in the first phase of the movement measured in the time frame of 160 ms. After the peak is reached, speed decreases in about the same time frame. During the execution, the average recorded acceleration was 78 m/s^2. The angular speed of the pelvis was also measured, and values obtained while performing a reverse punch were 12–16 rad/s.[12]

Echeverria and Santos evaluated the efficacy of computer vision algorithms in accurately detecting the various postures executed by karate practitioners during the dynamic motions involved in *kumite*. Researchers took into account the high level of explosiveness, variability of executed techniques (among which is *gyako tsuki*), and necessity for adaptation during karate fights. The classification algorithms coming from realistic karate performance situations in conjunction with non-labelled photos yielded positive outcomes. The authors concluded that movement detection systems can be applied in karate practice.[53] Venkatraman et al. also presented an independent and unconventional Punch-O-Meter system to monitor reverse punch speed and force. Following the identification of the optimal sensor setup and punching site, a series of experimental tests were conducted to measure the punch force of the *gyako tsuki* at six distinct speeds. However, the researchers in both studies were based on laboratory conditions.[54] However, the researchers based the tests on laboratory conditions.

The purpose of the research that was carried out by Quinzi et al.was to investigate the reliability of the correlation between lower limb maximal power and punch speed. This was to be done not only for individual actions, but also for a combination of *kizami tsuki* and *gyaku tsuki* in situations that were either static or dynamic. The results of this study indicate that there were notable associations between the maximal relative power of the lower limbs and punch speed across all tasks and settings. These findings suggest that the relationship between lower limb power and punch speed remains consistent even when considering combinations of punching techniques performed in dynamic conditions.[55]

Goethel et al. studied the phase relationship between the proximal and distal joints during the *gyako tsuki* punch, comparing elite and sub-elite karate athletes. The linear velocity peak of the wrist was measured. They found that coordinated motor patterns of performance become more stable and controlled due to experience. As a result, elite athletes achieve a linear velocity peak of the wrist significantly higher (7.3 ± 0.8 m/s) than the sub-elite group (6.1 ± 0.7 m/s). According to the authors, this kind of result can be attributed to the higher optimisation of the kinetic chain in the elite group, i.e., a better intra-segment coordination capacity. In that matter, the stability of coordinated patterns can be regarded as an element of technical quality.[34]

Venkatraman and Nasiriavanaki compared the attained speed and force in *gyako tsuki* performance with and without rotating the fist. The performance condition made a difference of 3.56% in the speed of the punch: the punch performed with rotation reached 5.33 ± 0.215 m/s, and the one without rotation reached 5.52 ± 0.212 m/s. Also, the force generated in the first case was higher.[56]

Quinzi et al. investigated if there is a connection between lower limb maximal power and punch speed while performing the combined technique in static and dynamic conditions. It was determined that lower limb maximal relative power and punch speed are significantly correlated regardless of task and condition applied. Besides, punch speed observed in the study ranged between 6.28 and 7.21 m/s, but what is particularly interesting is that the combination of punches *kizami tsuki* and *gyaku tsuki* led to an increase in punch speed when compared to using *gyaku tsuki* alone. For example, a combination of punches performed from a static position resulted in 6.69 m/s in contrast to *gyako tsuki* alone at 6.28 m/s, and similar results were obtained from a dynamic position: 7.21 m/s vs. 6.47 m/s, respectively.[55]

Analysing elite athletes' performance Marković et al. determined the differences in the temporal structure of the reverse punch in relation to the achieved maximal velocity. On the basis of the kinematic parameters and their temporal indicators, which create a recognisable time structure, punch could be categorised as slow, average, or fast. The study evidenced the median maximal velocity of the hand from the slowest to the fastest group as follows: 5.72 m/s, 6.37 m/s, and 7.11 m/s, respectively.[36]

The objective of the study conducted by Goethel et al. was to examine and contrast the abilities of karate athletes divided according to their competitive experience in terms of kinematic parameters, perceptual and reaction skills as well as neuromuscular control while performing a *gyaku tsuki*. The more experienced athletes demonstrated significantly greater values in nearly all performance indicators. The elite athletes demonstrated shorter time durations in perceptual and reaction skills. The sole notable disparity in the neuromuscular control parameters was observed specifically during the deceleration phase. In this phase, elite athletes exhibited a greater co-contraction index between the groups of muscles involved in punching. In summary, the more experienced athletes demonstrated superior reaction speed, wrist acceleration, and braking efficiency compared to the less experienced ones, resulting in a less detectable strategy for their opponents.[57]

2.5 Limitations of the Previous Research

As previously mentioned, the analysis of the kinematics of karate techniques is a subject of frequent investigation within laboratory settings.[58,59] Athletes in these situations are constrained in ways that are uncommon in actual combat. As a result, such surroundings may have an impact on the technique being researched.[58] The consequences are clear given that elite sports involve subtle adjustments and reactions to changes. Aside from that, it can be argued that there has been a lack of systematic research in the biomechanical analysis of reverse punch. For that reason, it is hard to structure the findings and offer a complete kinematic illustration of this technique. In particular, major problems are:

(1) Various sample and level of condition;

Differences in participant groups relate to gender and experience (including novices, regular practitioners, elite, and sub-elite athletes), while comparison conditions mainly relate to level of expertise,[7,34] task orientation,[13,52] or a combination of conditions (level of expertise-task orientation[50] or gender-task orientation[13]).

(2) Different test settings that affected the kinematic factors under observation;

The aims of the studies determined various test conditions (starting position, goal orientation, presence or absence of a target or a stimulus), which influenced the monitored kinematic parameters. Kinematic differences in reverse punch can occur as a consequence of numerous factors: experience,[7,34] competitive specialization,[11] overall timeline structure,[36] distance, primary orientation towards maximal speed or maximal impact in professional karate athletes,[13] or self-initiation or reactive executions drown by stimuli.[50]

In addition to the above, probably the most important issues are:

(3) Experimental setup and task specific conditions;

Different aims of the studies determined different test conditions that influenced the monitored kinematic parameters (executing a punch in the air, a punching pad, a wooden beam, or a platform). In addition, diverse types of measuring equipment were applied. Just to remind, VencesBrito et al.[60] investigated the kinematic and EMG patterns of *choko tsuki*, which was executed in a natural standing stance on a wooden board *makiwara*. Gothel et al.[34] were investigating the joint-phase relationship while executing the technique. The relationship between the proximal and distal joints was the focus of the investigation. Participants performed a RP from the fighting stance on an instrumented target, using visual stimuli. Audio and visual stimuli were used in the study of Martinez de Quel et al.[50] and RP was performed on a punching mitt fixed to a wooden beam in order to determine whether within-task expertise affects execution time in reactive and self-initiated movements. In the study of Loturco et al.,[13] participants, standing in a fighting stance, performed RP on the body of their opponent, having different goal and task orientations.

(4) Diversity of punch execution phases or kinematic parameters of the segment being studied;

It should be emphasised that RP kinematics has been observed and analysed in the various performance phases of execution and is influenced by experimental conditions. Meaning that the variables of interest (linear and angular velocity and acceleration) were calculated taking into account different referent points (pelvis, torso, shoulder, elbow, and fist), and time points in the movement performance. Just for an example, Martinez de Quel et al.[50] defined the movement time of the reverse punch as “time elapsed from movement onset to the moment of zero crossing in velocity” and the movement onset as “the first moment when the speed was more than 10 mm/sec for 40 ms consecutives”, while Fusch et al.[52] defined the time of the execution of RP as the absolute time [ms] from the first movement enabling anticipation of an attack to the instant when the punching fist hits the target” and the shift of the centre of body mass up to 4 mm was taken as the starting point of the punch.

2.6 Sensors Application in Sport Performance Evaluation

Tracking changes in relevant performance parameters is a sports necessity enabled by measurement.[61] So, the main question is how to overcome these limitations and whether kinematic sensors (KS) can improve the measuring process. The use of KS is rapidly expanding in a broad field of sport (taking into account elite, high-level sport and recreation).[4,5] Among others, the following causes stand out as the most important: overcoming the limitations of laboratory-based assessment and the constraints of conventional training methods founded on coaches subjective evaluation.[12,18,58] In order to be applicable, KS must provide assurance of their accurate use so as to meet high standards for reliable performance monitoring and evaluation. Such an approach leads to systematic and objective qualitative and quantitative analyses, as well as the association of science-based knowledge with practical application,[4,18,32,33,62] which is the ultimate goal.

Studying joint kinematics in the context of actual sporting activity is a difficult undertaking. The need to use cutting-edge approaches that have an impact on data collecting is the underlying cause.[14,18] Additionally, performance changes occur frequently and abruptly, which compromises the measurement's precision.[58] Further, motor tasks specific for the sport and kinematic parameters relevant for the analysis determine the most suitable measurement system, which always has to meet high precision criteria and reliability.[35] Such a system should ensure the athlete's unrestricted movement, whether it is performed in training sessions or competitions. This can be achieved by using ergonomic, wireless measuring instruments characterised by enough power and appropriate measurement capabilities.[14,18,63]

2.7 Sensors Application in Combat Sports

Inertial sensors are used in more than one area of combat sports studies (such as taekwondo, judo, boxing, and karate) to enhance the training[64] and competition process,[65] technical modelling,[66] equipment,[67] execution, and technique examination.[12,13,50,68–71] Different strategies have been used, including mounting wearable devices on athletic outfits, athletes, or both. Nevertheless, the use of KS is not extensive.

One of the possible explanations for the lack of such studies using KS is the sports-specific restrictions that combat sports impose on its use. Less than 3% of studies reviewed by Camomilla et al.[18] featured combat sports. The majority of existing sensors are rendered ineffective by high acceleration levels, quick and ballistic movements, and numerous rotations of the engaged segments of the kinetic chain, as seen in combat sports techniques.[18,72] When considering the use of kinematic sensors, the specificity of soft tissues must be taken into account. Namely, the motor task, in itself, sets certain requirements in terms of the location and the way of placing the measuring device.[18] Given all that, the topic's intricacy becomes clear. Finally, that raises the question of reliability and applicability of wireless sensors technology in the analysis of the combat sports techniques, particularly punches.

In high-level sports, an individual approach is of outmost importance. Such an approach should be directed towards a comprehensive analysis. In order for such an analysis to be productive, it needs to be focused on the critical stages of performing the technique. On the other hand, knowledge of impact biomechanics provides guidelines when choosing a measuring instrument with appropriate characteristics. The operating range (OR) and sampling frequency of the device will depend on the phase in which the kinematic quantities are measured. In the development phase of the punch, they are lower, while at the impact, the highest values are achieved; therefore, a higher OR is necessary. The same principle should be applied whether the focus is on a proximal or distal segment. In terms of the gradual growth in kinematic quantities, the phase before the impact might be regarded as developmental.[35] On the contrary, the final phase of execution is characterised by achieving the highest acceleration values;[73] hence, sensors that can register high kinematic values are needed. Previous research in combat sports, aiming for different performance features, shows diversity in device properties with an operating range of the accelerometer between ±3 g and ±2000 g, the gyroscope from 1000 deg to 4000 deg, and a sampling frequency of up to 5000 Hz.[72]

Understanding the biomechanics of the technique under analysis, as well as knowledge based on common practice, is supposed to provide a broader perspective regarding device properties, such as the number of necessary sensors and their positioning. Of course, the research goal issue stays open and should also be reconsidered in relation to these requests. Different studies employed a diverse model of sensor positioning, applying one measuring device or using a full-body model.[72] But the objective is to propose a reference body point that might provide illuminating data. Also, sensor-to-segment axis alignment is a critical feature that should be considered when predicting joint kinematics with inertial sensors.[59] However, obtaining such data is possible only if the positioning of the device has no impact on its output.[72] To put it another way, the kinematic quantities at the specified body attachment position must not be greater than the device's dynamic ranges. Additionally, this means that the site must satisfy the requirements for a safe connection. In order to assure firm connection during ballistic motion, additional fastening kit should be taken into account. Of course, main condition is to enable athletes to perform the technique without interference[74] in the way they normally do it in training and competition.

3. Research Problem, Subject, Aims and Tasks

The technical aspects of the reverse punch aiming at the body, the most dominant punching technique in sports karate fights, are the research problem.

To be more specific, the subject of the research is the quality of technique across several performance modalities.

The aim of the research is to assess the differences between the kinematic and temporal indicators of RP in different modalities by applying the kinematic sensor technology in realistic performance conditions.

The following research tasks arise from the above:

- Sample recruitment;
- Sample data collection (body weight, body height, age, years of training and competition experience, dominant fighting stance);
- Estimation of kinematic and temporal characteristics of the punch in different performance modalities;
- Signal processing;
- Statistical data processing and analysis

3.1 Study #1

The point-worth technique is what makes the difference between victory and defeat. In order to perform such a technique in an elite-level competition, every aspect of its execution has to meet the highest standards that lie on the kinetic and kinematic foundations.[4,13,68]

To have a comprehensive understanding of the intricacies involved in punches, it is imperative to conduct measurements in a training setting that closely replicates real-life conditions. A reliable instrument ought to be the first step in achieving this objective. This necessity is especially pronounced in combat sports, where research in real combat situations is particularly important.[12,13]

The objective of this study was to evaluate the metric characteristics and reliability of kinematic sensors in specifically created karate tests. Namely, the study aimed to evaluate the reliability of kinematic sensors in accurately capturing acceleration data during the execution of punches. The punch performed was *gyako tsuki*, the most common karate technique.

3.2 Study #2

Elite karate athletes are consistently confronted with the demand to enhance their scoring capabilities in dynamic fighting surroundings. In order to enhance technique, there is a requirement for a fresh methodology approach that encompasses data collection and comprehensive analysis of punch execution.

The potential of the Internet of Things (IoT) to offer a feasible resolution for this intricate issue is worth considering. Yet, the specificity of combat sports as well as the high demands of elite sports make research strategies take into account numerous factors.[12,14,18,58,63,72] Considering the biomechanical aspects of reverse punch, the technical characteristics of wearable kinematic devices, the dynamism of karate combat, scoring requirements, training, and competition surroundings, this study proposes a novel method for data acquisition.

The main aim of this study was to achieve the following objectives: (i) obtain the relevant parameters required to improve technique by using specially designed assessments; (ii) perform a thorough analysis of the initial stage of the reverse punch as a basis for creating an individualised training programme; and (iii) propose the specific integration of wireless sensor devices based on the biomechanics aspects of the punch.

3.3 Study #3

There hasn't been a lot of research done on how joint motion affects the punch's effectiveness before impact. The same can be said about the relationship that exists between the kinematic and temporal characteristics of a reverse punch (RP), which is what ultimately decides whether a point will be scored or not.

It is known that RP has a segmental structure.[35,36,73] But impact has been the main focus of the research up to date. Elite karate athletes exhibit faster reactions and acceleration of the wrist, making their technique less noticeable to opponents.[34] They also have greater shoulder extension and generate a high preferred velocity for joint movements.[75] The punch kinematics are influenced by different task orientations and conditions of execution, such as the primary orientation towards force or speed at a fixed or self-selected distance.[13] In elite athletes, the peak wrist linear velocity can reach up to 7.3 m/s.[12] Competing experience also affects punch execution.[57]

The referred studies were conducted on a diverse sample, applying a variety of methodological approaches and not taking into account the developmental stage of the reverese punch. Hence, the objective of the present study is focused on variability as well as correlation between observed kinematic parameters and accompained temporal indicators of body and hand in the initiation of the punch execution.

4. Hypotesis

Based on a review of a previous research, the following hypotheses have been set:

HG – IMU sensor technology is valid and discriminatory with the respect to the specific indicators of the reverse punch and within different modalities of performance.

H1 – There is a difference in the kinematic parameters in the developmental phase of the reverse punch between the tests.

H2 – The appearance time of the kinematic events is structured in a recognisable pattern.

H3 – There is a correlation between the kinematic and temporal parameters of the body and hand in the developmental phase of punch.

5. **Study #1** Vuković V, Dopsaj M, Koropanovski N, Marković S, Kos A, Umek A. Metrical characteristics and the reliability of kinematic sensor devices applied in different modalities of reverse punch in karate athletes. *Meas J Int Meas Confed*. 2021;177. https://doi.org/10.1016/j.measurement.2021.109315

This study addresses the problem of data acquisition under the realistic sports settings. The study's objective is to assess the metrical properties and the accuracy of the measurement tools used in particular karate assessment. The need to perform kinematic measurements under the same or as close to conditions as training and competition is the main motive for this research.

5.1 Introduction

Karate and boxing, as well as some other combat sports, have its own specifics, but their common and most prominent characteristics are punches.[4] In addition, the karate technique incorporates a martial art philosophy that is summarised in the idea of one lethal strike. Obviously that cannot be the outcome of the sports fight, even though this intention has to be recognised and controlled in the pointing technique. Only efficient technique is point worth. Such a technique is supported by the appropriate stance with the centre of mass closer to the ground, achieved on account of the length.[5] Fighter is at constant pressure to focuses all their potentials and regrouping them in a limited time. As a result, technique is performed in a time interval measured in milliseconds. Without kinematic analysis, it is impossible to comprehend such a complex process. The researchers combined various measurement tools[5,9,10,60,76] due to the intricacy of the human systems that interact with one another.[6] Such an approach required that research be conducted in the laboratory with the equipment that needs application expertise. The problem lies in the limited application of such a method. Namely, it is impossible to obtain data in conditions that correspond to a realistic fighting environment. Some researchers, nonetheless, underline the significance of the data acquisition in training and/or competition settings.[12,13] Technology utilising wearable sensing could be the answer. Increased application of inertial measurement units (IMUs) has made them an integral part of performance analysis in sport science.[14–16] Although the sensor specifications recommend these measuring instruments for valid and reliable data collection, combat sports science has not yet fully embraced wireless kinematic technology.[18]

IMUs are used to improve training method[64] and competition practice,[65] performance analysis and technique evaluation,[12,13,50,68–71] equipment,[67] and technical modelling[66] in a variety of combat sports studies. Various methods have been employed. Depending on the aim of the study, mounting method differs. Wearable sensors are used on: i) fighting equipment, ii) fighters, iii) or combining both. Fallowing kinetic and kinematic quantities were recognised as important in combat sport studies: translational and rotational accelerations, force and angular velocities.[4,13,68] Acceleration is identified as a primary factor enhancing efficiency of karate punching technique. Additionally, dependence of acceleration and upper- and lower-body strength and power is verified under various conditions.[13]

Karate can be characterised as an open skill. Such a classification indicates the nature of the sports fight (common use in Japanese language – *kumite*), which is reflected in the constant changes in the conditions imposed by the competitors. Fighters must effectively manage multiple concurrent pieces of information in order to progress against their opponent and adjust their tactics as necessary.[29] The unpredictability of the fighting conditions is reflected in constant shifting between the different types of actions performed from the various distance. Nonetheless, the high frequency and speed of techniques remains the most dominant feature of the karate fight.[13] Regardless of the modality of scoring, punches are the most frequently used technique.[27] One of the reasons might be that kicking techniques demand more time to execution.[13] That doesn't necessarily mean that they are easier to perform. Gradual integration of the bodily segments in the punch, as well as their coordination pattern, suggests a potential range of performance variability.[4,13] The punch pattern consists of a sequence that is initiated with movement of the rear leg ankle and is followed by the inclusion of the knee and hip. The final points of the kinetic chain are located in the upper limb performing the punch, in this order: shoulder, elbow, and wrist. Human system is complex structure that acts in synergy. Human locomotion depends on each and every one of them, and their specifics affect the movement.[6] In terms of complexity and the issue with degrees of freedom,[31] punches demand caution in the analysis. Researches support these assumptions in various ways. It is founded that technique execution is affected by experience[77] or conditions of performance (such as being able to choose the time[50] of execution, distance, or goal[13]).

Elite karate athletes most commonly use RP (in Japanese language *gyako tsuki*), as a pointing technique. The rate of occurrence is more than 60% of the time. Also, RP aiming the opponent's torso in comparison to RP aiming the opponent's head is more frequent at world and European level competitions.[27] On the base of the evidence it can be argued that RP is punch with consistent acceleration. Also, in the first 160 ms of the punch execution, the hand speeds up to 12.5 m/s.[12] A combat stance *(fudo dachi)* is used to deliver the reverse punch. The leading arm takes the guard while the punch is executed with the back hand. Through particular phases of RP, movement patterns can be established. Features that reveal a general pattern of performance appear at each step enabling the analysis. In this process, it is important not to forget the combined influence of different factors on RP. As a consequence, kinematic parameters like acceleration may be impacted by changes in the movement pattern.

The study aimed to assess the metrical properties and reliability of Kinematic Sensors (KS) in particularly designed karate tests. The goal was to evaluate the reliability of KS in acquiring acceleration data during RP, the most frequent scoring karate technique. This advanced technology is crucial for predicting biomechanical system trajectory and behaviour, making it essential for training and competition.[78,79]

5.2 Materials and Methods

In the current study, KS technology has been used to quantify segmental acceleration in various modalities of the reverse punch executed by karate practitioners.

5.2.1 The Research Sample

A Serbian national karate team took part in the study. The fourteen male athletes, senior and cadet, were selected. Such a choice was made on account of the rules of the karate competition, which equalise them in terms of scoring. Practically, it means that the technical standards are what determine whether or not a point is given, not the competitors' ages.[25]

The sample's basic features included age of 17.53 ± 3.02 years, height of 1.78 ± 0.10 m, and body mass of 70.31 ± 15.67 kg. At the time of the research, all participants were in good health, free from any injuries, and engaged in frequent practise.

All participants completed written informed consent forms following thorough explanations of the study's risks and benefits. The study was carried out in accordance with the ethical principles outlined in the Declaration of Helsinki, and it received approval from the Faculty of Sport and Physical Education's Ethics Research Committee (Project III47015, Protocol No. 484).

5.2.2 Measurement Methods

Field testing was performed by the same qualified examiners. Before the testing, participants went through a 15-minute standardised warm-up. Tests were performed from a front-left stance without any additional movement apart from what was foreseen by the test. RP was performed with the right hand, taking into account the fact that it was the dominant hand.

To enhance test control and identify punch phases, two GoPro HERO 6 and Logitech C920 HD PRO cameras were used to capture the execution of RP in all stages, anteriorly and posteriorly. Participants were positioned two metres from the cameras, which were mounted on a tripod and 1.3 metres off the ground.

The three WKF experienced referees oversaw and evaluated the technique performance subjectively. Only punches that met strict technical requirements (i.e., were executed in a way that was worth points) were considered and subjected to further analysis.

Participants underwent a test consisting of three consecutive punches performed in three different ways:

(1) Participants in the *gyako tsuki chudan* test without hip rotation (GTCNH) stood in a basic left stance. The *zenkotsu dachi* comprises back leg straight and hips at a 90-degree angle. While the right arm was in flexion, the left arm was at rest alongside and close to the torso. The right arm was at a 90-degree angle and resting on the body. Participants maintained their starting position and executed three consecutive punches 5 s after hearing a signal.

(2) Participants in the *gyako tsuki chudan* test with hip rotation (GTCH) stood in a left combat stance. The *fudo dachi* comprises back leg bended, and both hips positioned at

the angle relative to the direction of stance orientation and movement path. The guard was adopted. The athletes were able to execute a punch that included the whole kinetic chain with the features mentioned above thanks to their stance and arm position. The remainder of the testing procedure was identical to the first test.

(3) Participants in the *gyako tsuki chudan* test with motion (GTCIM) kept the same initial position as in second test. Athletes were asked to conduct three successive punches in motion. During the punch execution, athletes were sliding forward and back relative to the starting position.

5.2.3 Devices

Two wireless devices were used in study and such reasoning was based on biomechanical knowledge. They were positioned as follows: 1) on the trunk of an athlete, corresponding with the centre of gravity (the exact location was within the second and third lumbar vertebrae); 2) on a punching fist within the second and fourth osseous metacarpals (Figure 5.1: (a) and (b), respectively). For a certain application, it was determined that the combination of presented positions was the most advantageous and instructive. Fastening kit was used for safe positioning and high output.[74] In addition, it has to be stated that different devices orientation was irrelevant due to 3D unit with equivalent axes responsiveness.

The signal coming from KS were timed with the ones coming from video cameras. For that purpose the LabView application was used. Acquired data was saved in files on a personal computer, waiting for analysis. The 6DoF IMU sensor LSM6DS33 had buil-in absolute orientation sensor BNO055, dynamic range of accelerometer +/- 16g and, DR of gyroscope +/- 2000 dps. While the sampling frequency of KS attached to the hand was 200 Hz, the one attached to the back was lower, 100 Hz. The acquired data is read and transferred by the microcontroller using an incorporated WiFi module. This was done by the UDP protocol.

Downstream processing and examination was done by the MathCAD package. The analysis included: (a) frontal movement's primary source of hand acceleration; (b) the absolute hand acceleration, and (c) the absolute linear acceleration of the body. The signals are filtered with a Butterworth 5th order low-pass filter. The cut-off frequency is 40Hz. When the hand stops, there is a strong pulse of absolute acceleration that coincides with the hand impact. The threshold triggering method determines impact time, with a hand acceleration threshold value of 15 g_0, as determined by studies. The impact detection technique employs unfiltered absolute hand acceleration signals, incorporating filtering delay in analysing the temporal properties of filtered signals.

The analysis of motion variables involves shifting signals to the arm impact moment, with a defined time window of N = 50 samples. Kinematic variables analysis focuses on local maximum acceleration and impact time, using the same algorithm for all three pairs of variables.

Figure 5.1. Location of the KS: (a) On the trunk. (b) On the upper side of fist executing the punch

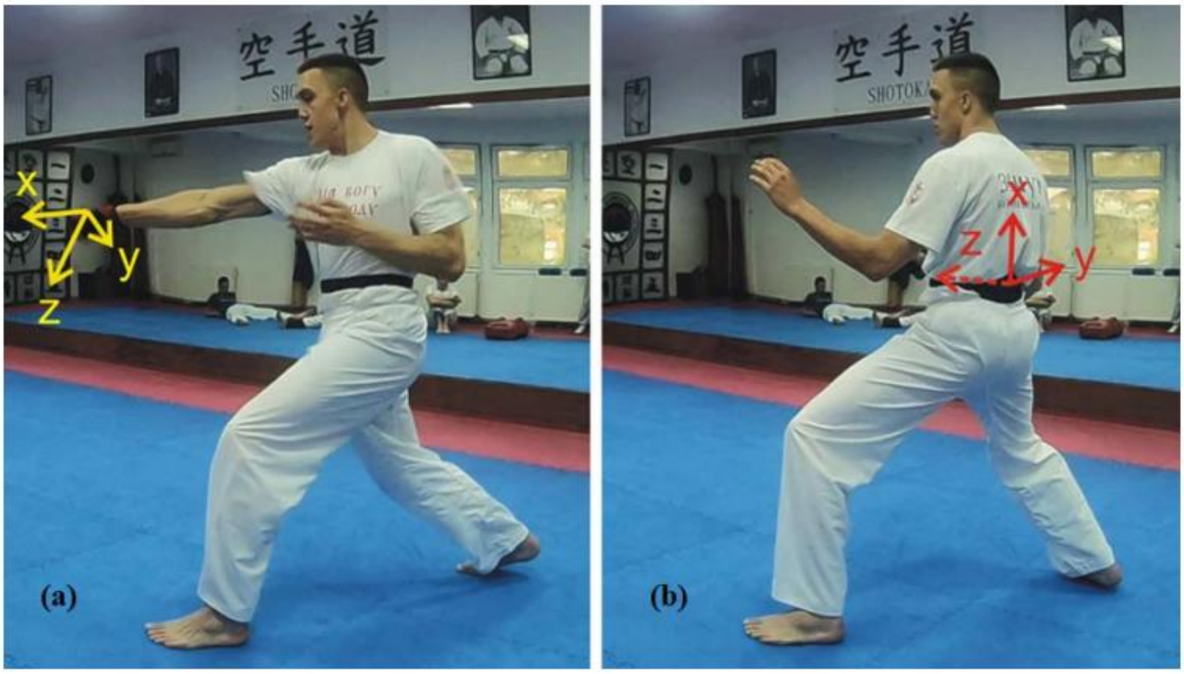


Figure 5.2. The orientation of the devices. (a) On the hand. (b) On the trunk

5.2.4 Variables

A number of acceleration-related variables for the torso and hands were measured. The origin for precise time measurement is chosen to be the moment of impact. The hand's measured absolute acceleration signal is used to determine the impact time. The following six variables are derived:

- a maximal absolute acceleration of the hand movement (AbsAccH) expressed in standard gravity (g_0),

- a maximal acceleration of the hand movement in the horizontal axis (AccHx)
- expressed in standard gravity (g_0),
- a maximal absolute acceleration of the body movement (AbsAccB), expressed in standard gravity (g_0),
- the time of maximal absolute acceleration of the hand movement (AbsAccH) until the impact expressed in seconds (s),
- the time of maximal acceleration of the hand movement in the horizontal axis
- (AccHx) until the impact expressed in seconds (s), and
- the time of maximal absolute acceleration of the body movement (AbsAccB) until the impact expressed in seconds (s).

Figure 5.3 shows the variables that were derived from the recorded acceleration signals in one test measurement (GTCNH, second try). In all three different modalities (GTCNH, GTCH, and GTCIM), the obtained variables were measured in the first stage of GTC execution, before the impact.

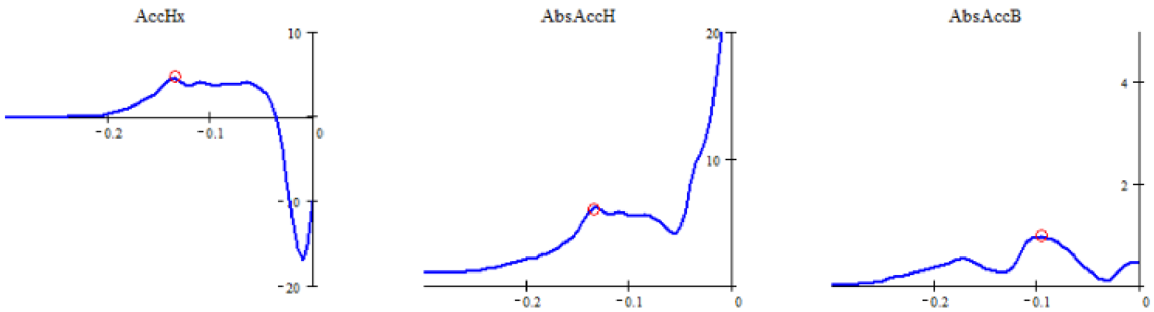


Figure 5.3. Time is assessed in relation to the impact using recorded acceleration signals and inferred kinematic variables (red circles). Standard gravity [g_0] is used to represent acceleration, while time is stated in seconds

5.2.5 Statistical Analysis

The study used descriptive statistical analysis to analyse raw data, checking for normality using the nonparametric Kolmogorov-Smirnov. Using a test-retest methodology, the sport-specific dependability of Kinematic sensors was assessed over the course of three repeated punch trials. The intraclass correlation coefficient (ICC) was calculated. Internal consistency was assessed using Cronbach's Alpha, with reliability levels ranging from 0.50 to 0.90.[80] To determine how closely two variables are related, the Pearson correlation coefficient was utilised. To determine the general association strength, the average correlation in relation to the inter-item correlation matrix was determined. ANOVA was used to analyse any potential differences between the observed variables. With a 95% chance of statistical significance,[81] the statistical analyses were carried out using IBM SPSS Statistics and Microsoft Office Excel 2007.

5.3 Results

Table 5.1 shows basic descriptive analysis. The mean ± SD of GTC considering each of the three modalities ranges between 6.967 ± 1.740 g_0 and 8.245 ± 2.071 g_0 for the peak of acceleration and from –0.094 ± 0.021 s to –0.128 ± 0.055 s for the time of occurrence. Acceleration values for dominant axis of hand motion ranges between 4.596 ± 3.120 g_0 and 5.158 ± 3.326 g_0 for the peak of acceleration and from –0.078 ± 0.034 s to –0.104 ± 0.030 s for the time of occurrence. The mean ± SD of GTC for absolute body acceleration ranges from 1.141 ± 0.441 g_0 to 2.706 ± 0.780 g_0 for the peak of acceleration and from –0.045 ± 0.055 s to –0.092 ± 0.060 s for the time of occurrence.

In respect to all technique modalities, Table 5.2 shows the accuracy of the KS in measuring the acceleration of the hand and body along with the time of occurrence. Eight kinematic variables, or 44.4% of the total variables evaluated, showed good reliability (ICC = 0.75-0.90) in regard to the qualitative criterion of ICC significance. But for 10 kinematic variables, or 55.6%, excellent reliability (ICC > 0.90) was verified. It's interesting to note that the reliability values are lowest for the time of occurrence and highest for the peak of acceleration. As can be shown in Table 5.2, the F Test with True Value 0 reveals that all kinematic variables have been accurately evaluated using KS with statistical significance $p < 0.001$.

Table 5.1. The mean and standard deviation, were computed for the kinematic variables across all three repetition time points and modalities of the GTC technique

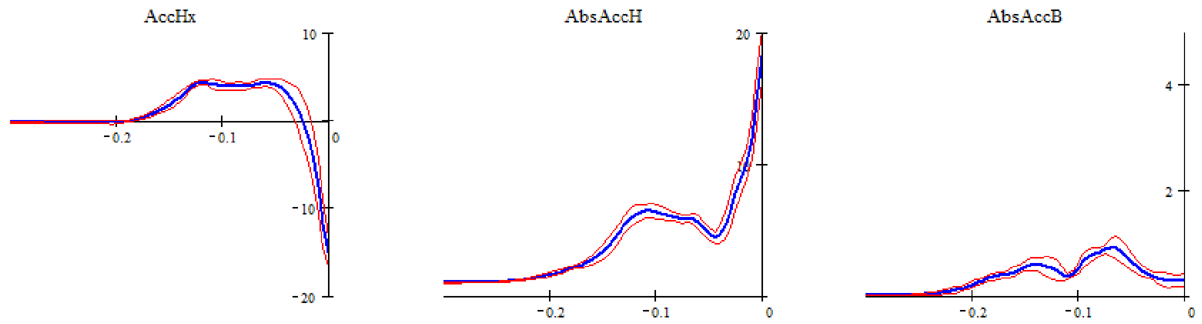
			AbsAccH			
	t_1 [s]	t_2 [s]	t_3 [s]	$AccV_1$ [g_0]	$AccV_2$ [g_0]	$AccV_3$ [g_0]
GTCNH	–0.094 ± 0.029	–0.094 ± 0.021	–0.101 ± 0.031	7.053 ± 1.362	7.014 ± 1.456	6.967 ± 1.740
GTCH	–0.104 ± 0.044	–0.105 ± 0.051	–0.096 ± 0.050	7.378 ± 2.076	7.783 ± 1.512	7.703 ± 1.804
GTCIM	–0.119 ± 0.053	–0.110 ± 0.049	–0.128 ± 0.055	7.895 ± 1.994	8.245 ± 2.071	7.860 ± 2.472
			AccHx			
	t_1 [s]	t_2 [s]	t_3 [s]	$AccV_1$ [g_0]	$AccV_2$ [g_0]	$AccV_3$ [g_0]
GTCNH	–0.097 ± 0.024	–0.094 ± 0.023	–0.104 ± 0.030	4.865 ± 2.946	4.771 ± 3.077	4.596 ± 3.120
GTCH	–0.102 ± 0.041	–0.093 ± 0.048	–0.088 ± 0.045	4.813 ± 3.232	5.003 ± 3.278	5.158 ± 3.326
GTCIM	–0.078 ± 0.034	–0.074 ± 0.028	–0.081 ± 0.026	4.735 ± 2.925	4.801 ± 3.161	4.665 ± 2.934
			AbsAccB			
	t_1 [s]	t_2 [s]	t_3 [s]	$AccV_1$ [g_0]	$AccV_2$ [g_0]	$AccV_3$ [g_0]
GTCNH	–0.051 ± 0.477	–0.057 ± 0.053	–0.057 ± 0.048	1.141 ± 0.441	1.322 ± 0.649	1.273 ± 0.539
GTCH	–0.092 ± 0.060	–0.070 ± 0.071	–0.078 ± 0.065	2.402 ± 1.075	2.555 ± 0.801	2.599 ± 1.074
GTCIM	–0.045 ± 0.055	–0.050 ± 0.066	–0.056 ± 0.068	2.305 ± 0.620	2.706 ± 0.780	2.501 ± 0.798

Table 5.2. Statistics on reliability according to the GTC technique's factors and modality

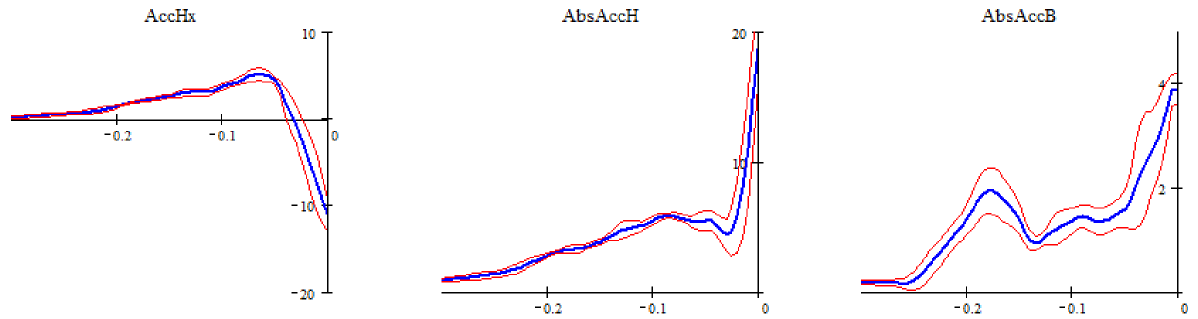
				ANOVA		ICC	ICC 95% Confidental Interval		F Test with True Value 0	
			Cronbach's Alpha	F relation	p value	Average Measures	Lower Bound	Upper Bound	F value	p
AbsAccH	GTCNH	t_{1-3}	0.845	0.680	0.515	0.826	0.574	0.940	5.76	0.000
		Acc_{1-3}	0.910	0.045	0.956	0.902	0.760	0.966	10.22	0.000
	GTCH	t_{1-3}	0.870	0.467	0.632	0.862	0.662	0.952	7.245	0.000
		Acc_{1-3}	0.943	1.168	0.327	0.937	0.845	0.978	15.85	0.000
	GTCIM	t_{1-3}	0.904	1.653	0.211	0.903	0.761	0.966	10.27	0.000
		Acc_{1-3}	0.907	0.537	0.591	0.902	0.759	0.966	10.18	0.000
AccHx	GTCNH	t_{1-3}	0.764	1.048	0.365	0.756	0.401	0.915	4.09	0.001
		Acc_{1-3}	0.987	0.744	0.485	0.987	0.968	0.996	77.71	0.000
	GTCH	t_{1-3}	0.885	1.122	0.341	0.882	0.711	0.959	8.49	0.000
		Acc_{1-3}	0.980	0.670	0.520	0.980	0.951	0.993	49.72	0.000
	GTCIM	t_{1-3}	0.842	0.451	0.642	0.829	0.582	0.941	5.86	0.000
		Acc_{1-3}	0.990	0.238	0.790	0.990	0.975	0.996	96.58	0.000
AbsAccB	GTCNH	t_{1-3}	0.951	0.472	0.629	0.950	0.878	0.983	20.06	0.000
		Acc_{1-3}	0.917	1.651	0.211	0.902	0.759	0.966	10.18	0.000
	GTCH	t_{1-3}	0.839	1.084	0.353	0.844	0.618	0.946	6.42	0.000
		Acc_{1-3}	0.848	0.409	0.668	0.836	0.597	0.943	6.09	0.000
	GTCIM	t_{1-3}	0.927	0.571	0.572	0.928	0.823	0.975	13.85	0.000
		Acc_{1-3}	0.782	2.251	0.125	0.780	0.459	0.923	4.54	0.001

Figure 5.4. shows the motion consistency and individual characteristics of an athlete according to the applied modalities of the GTC. The individual characteristics are reflected in the acceleration and time parameters.

GTCNH:



GTCH:



GTCIM:

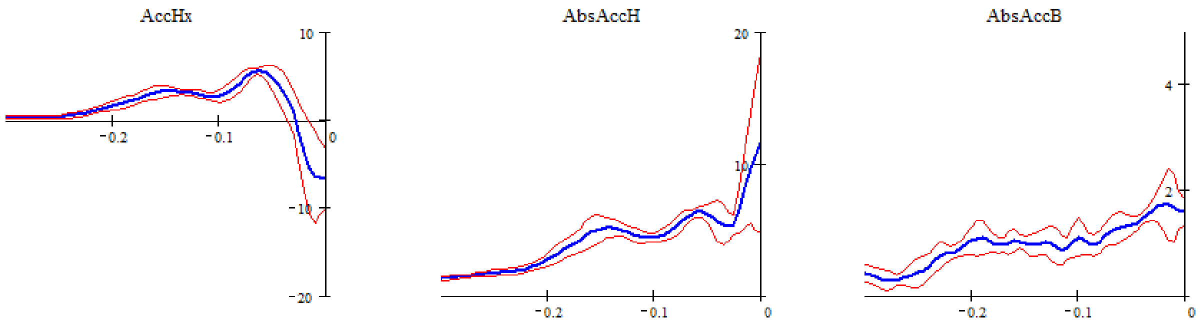


Figure 5.4. For a single subject, motion consistency and individual signature according to the three GTC modalities (GTCNH, GTCH, GTCIM). The blue line represents average value, and the red ones average value ± 1 SD

The study calculates average correlations between variables in three modalities (GTCNH, GTCH, and GTCIM) and analysed variables (AbsAccH, AccHx, and AbsAccB). Results show a higher correlation of acceleration (0.804) in compare to time (0.698). The highest homogeneity in acceleration was found with the AccHx variable (0.959), while the highest homogeneity in time was detected in AbsAccB (0.770). The highest summary correlation coefficient was found between 1 vs. 2 attempts for GTCNH (0.811) and GTCH (0.791). When comparing 2 to 3 attempts, the GTCIM's greatest summary correlation coefficient was 0.801.

5.4 Discussion

The current study's objective was to assess the metrical properties of KS in a particular karate test consisting of *gyako tsuki* performed in three different ways. The evaluation of kinematic sensors is crucial, as they offer an innovative strategy for understanding the kinematic patterns of karate technique. However, before their use becomes conventional, they must be subjected to testing. The study's key results indicate that kinematic sensors are reliable instruments and can be applied to elite athletes. To be clear, good reliability is determined in eight and excellent reliability in ten kinematic variables in terms of the qualitative ICC criterion (Table 5.2). A deeper look into the results shows that the majority of the data (namely 75%) confirming good reliability is on account of the time component. As for the excellent reliability, a slightly smaller percentage is on account of the acceleration. Focused testing of elite athletes implies comprehending the origins of technical variations. Although analysing technique divergence was not the goal of this study, the results do demonstrate that it is possible to identify technique discrepancy. Figure 5.4 illustrates this point: the more intricate the structure of the motion, the more pronounced the consistency change. This indicates that the processes of the locomotor system's adaptive behaviour are activated in a way that engages a number of systems at once. In order to maintain balance, it is required to resist external pressures. However, at the same time, it is important to place the body segments in relation to one another and the surroundings and project the centre of mass appropriately.[6] The study shows that caution is needed in regard to the variability of the time variables. In comparison to acceleration, the time parameter has lower stability. Knowing that, it is expected that the ICC will be lower or more widely spread (Table 5.2). This also suggests that, despite the punch structural complexity, the ideal value of acceleration will probably be attained. Nevertheless, the best moment for the peak of acceleration is still a controversial issue. The results support the use of wearable sensors as a reliable instrument for measuring kinematical parameters. As such, they can be used in the detection of small and barely noticeable technical differences. Such knowledge can help in discovering the causal relationship globally.

In general, GTCIM and AccHx (compared to the Acc_{1-3}) have the highest value for reliability in respect to all applied modalities and examined kinematic variables, with a difference between lower and upper bound true mean of just 0.021 g_0 (Table 5.2). Following the GTCIM's excellent reliability in relation to AccHx and Acc_{1-3}, GTCNH and GTCH likewise exhibit excellent reliability. Such findings suggest that the measurement characteristics of wearable devices on the dominant axis of the punch are reliable. Further, this means that athletes produce the least deviation when they execute the technique along the prevailing axis of motion. Even the least technically proficient athlete can execute GTCIM in a manner that results in more than 97.5% resemblance. It is logical to suppose that techniques' variations and deviations will happen more frequently on a non-dominant plane. This is supported by findings for the same modality in relation to vertical, lateral and horizontal plane. Namely, reliability gets down to 75.9%. Exactly what such results suggest is the sensitivity of the device and its' capability to detect differences in athletes performance with precision. It becomes more obvious that the development of a system able to accurately measure relevant parameters of punch execution is of outmost importance. The final goal is that the electronic system is able to precisely acquire data that differentiates athletes in regard to technical quality. In the final stage, such findings lead to a more sophisticated training method. Elite athletes, in order to reach and stay at the top, require an individual approach. But above all, objective assessment is the basis for personal adaptations and training aimed at improving a technique.[79,82]

As can be seen from Table 5.2, the results of the study confirmed the lowest reliability when KS was applied in the GTCNH modality, including acceleration on the dominant axis (relative to $t_{1\text{-}3}$). A clear and precise arm movement was primarily responsible for the reliability of 75.6%. GTC, excluding the lower body, evaluates upper limb motion quality. An efficient punching technique is thought to primarily come from the lower body.[4] Boxers and other throwing or striking athletes use their lower extremities to produce strong punches; this is a principle seen in sports that feature obvious ballistic movements.[83] In terms of GTC, movements of the hip and pelvis have an impact on a distal segment in a kinetic chain. This influence is reflected in the change in angular velocity.[7] Kinematic indicators are directly influenced by the reaction forces that the legs produce when they are conveyed from the ground to the upper limbs.[13] In this process, time plays an important role. Slower baseball pitchers, for instance, were shown to exhibit a particular tendency as compared to those attaining greater ball velocities. Namely, in the first case, the highest value of ground-reaction forces is always registered sooner in the performance sequence.[84] This is crucial when considering how force and kinematic data relate to one another.

Taking into account this explanation, in the light of the GTCNH test, one can draw the conclusion that the principal force generator is excluded from the punch, which is documented by the results in Table 5.2. Specific test organisation and measurement settings enable reliable inspection of the acceleration curve. Though the level of reliability varies, the same applies to the time parameter. It can be concluded that, regarding the arm movement, KS shows excellent reliability in relation to Acc and good reliability in relation to time. Introducing punch modalities, which activate the whole kinetic chain, affects ICC values. As can be seen in Table 5.2, ICC arises or becomes less widely spread. In a practical sense, this is significant information. It is not important just to have a reliable measurement tool. It is more important to know how to use and interpret data, especially knowing that punch shortcomings can be covered to a certain degree. In that sense, data coming from down part of the kinetic chain could provide more valuable details for a wider inquiry. However, because the kinematic devices applied in the study are sensitive to the athletes' personal execution signatures, it can be claimed that the data gained using this method in general is useful and instructive. These results are all the more noteworthy given the intricacy of multimodal kinematical structures and the range of experience levels.[85]

It is possible to assess a number of trials in relation to modality using calculated average correlations in relation to the ICC matrix. According to the findings, there is a stronger association between variables related to acceleration than to time. These results demonstrate once more that acceleration is a more trustworthy metric for identifying punch differences. From this perspective, stability and reliability could be assigned to acceleration as the main characteristics indicating divergence in technical performance. This can be brought on by the athletes' experience or by unique aberrations in their kinetic chain punch structure. For instance, it is reported that novice fighters tend to become more rigid during the entire motion (punch or kick).[12] This type of performance slows down a punch, and the acceleration profile shows it. The results of the current study imply that the timing of the acceleration peak is important. However, compared to acceleration, it is a less sensitive metric. The true meaning of this finding is that when analysing techniques, one should be careful in the interpretation of data. Not taking into account the acceleration profile could be misleading. Technique strategies are more likely to be masked by time, while acceleration values more obviously show how a kinetic chain's inclusion or exclusion of segments affects a technique. Additionally, AccHx was identified as the variable with the highest homogeneity.

Moreover, differences are noted between the modalities. The correlations demonstrate that finding the GTCNH's or GTCH's ideal indicators requires two trials. In GTCIM, 2 vs. 3 tries had the highest correlation when compared to the preceding two modalities. The findings clearly suggest that a technique performed according to the GTCIM requirements has to be executed three times. It is necessary in order to obtain information that is reliable. But only the best among the three tries should be taken into account. According to expectations, getting pertinent technique indicators for GTCNH and GTCH should require fewer attempts; this study supports it. GTCIM is the most difficult modality to do from a biomechanical standpoint since it has the most variables that might change how a task is ultimately carried out, either because certain kinetic chain components are excluded or included or because a technique is inconsistent. The last one describes circumstances in which changes take place as a result of a different level of expertise, experience, or ability to respond to body adjustments in a subsequent performance. Therefore, more attempts are required to obtain more trustworthy data.

Limitation

It was not possible to stratify participants by age because of the small sample size. Future research should consider a large number of participants, including individuals of various ages, levels of competitiveness, and athletes competing in both kata and *kumite*. In order to comprehend the biomechanical base of the reverse punch, it would also be intriguing to collect kinematical data from the lower part of the kinetic chain and undertake analysis that takes into account various modalities of *gyako tsuki*. Future testing should incorporate other technical modalities that closely resemble actual training and competitive settings in this regard. To be specific, different forms of motion, a punching target of a different kind, and a diversity of conditions may each have a varied impact on kinematic indicators.

5.5 Conclusion

It has to be emphasised that most research that has considered the same problem, up to this point, has taken place in lab settings. In this aspect, there is a dearth of data based on the actual *kumite* environment, as shown in the study. These findings are therefore instructive in a number of ways. To the best of our knowledge, the existing karate practice does not yet specifically and regularly utilise sensors. The results of this investigation suggest that KS could be used to change such evidence. Data acquired in actual *kumite* environments can be used as a basis for developing a training process. Coaches and karate competitors who are focused on high-level performance may be interested in inexpensive, portable, lightweight, and easy to use gadgets. In-filed collected data enables objective assessment, aids in quantifying kinematics, and transforms data into knowledge-based and practically useful recommendations.

The reliability of the tested kinematic sensors in this research has been proven for the punch aimed at the body in three specific tests. The study found high statistical significance in measurement reliability across all variables, with good reliability observed for eight and excellent reliability for ten kinematic variables. It can be concluded that this study helps to comprehend the patterns of technique execution, which advances professional development and performance objectification. The KS used in this study can be seen as a sophisticated measuring tool that successfully overcomes the limitations of combat sports. Apart from that, these devices offer a trustworthy foundation of knowledge for effective training planning for elite athletes. The presented wearable devices are highly reliable and applicable, but above all, easy to use.

6. **Study #2** Vuković V, Koropanovski N, Marković S, Kos A, Dopsaj M, Umek A. Specific Test Design for the In-Depth Technique Analysis of Elite Karate Competitors with the Application of Kinematic Sensors. *Appl Sci*. 2022;12(16). https://doi:10.3390/app12168048

Karate athletes face permanent pressure to improve scoring in changing fighting conditions. To improve technique, a novel approach to data acquisition and in-depth analysis of punch execution is proposed. This study focuses on the developmental phase of punch and key parameters for execution in realistic conditions, represented through ten specific tests, i.e., modalities of execution.

6.1 Introduction

Elite athletes maintain high training standards as they strive to consistently outperform their previous performances. Coaches' arbitrary assessments determine the standard training procedures. A step forward toward an advanced approach leading to standards that overcome this traditional practice[86] is in-depth technique analysis. It is hard to analyse combat sports techniques for many reasons. Some of them involve numerous and diverse methodological approaches.[72,87] The same applies to the reverse punch (RP) which is the most frequently used technique in karate combat.[27]

Elite-level karate combat is distinguished by its tendency for a variety of fighting circumstances.[88] It can be argued that direct attack accounts for the greatest number of scores.[27] Nevertheless, the variety of pointing actions is not limited to that.[26,27,89] Therefore, finding and using appropriate solutions is permanent.[26,29] The effectiveness of an athlete's scoring hinges on his or her capacity to adjust.[29] The aggravating circumstance is that all this happens in limited time intervals. Apart from that, the level of intensity in combat actions is very high.[26,89,90] Therefore, investigating and analysing RP in actual combat and training settings would be advantageous in order to address the problems that, due to their complexity, were treated independently in earlier studies.[12,13,50,51,66,77,91]

The Internet of Things (IoT) might offer a suitable answer for such a challenging issue. The field of protocols and applications, which encompasses a wide range of interconnected computer networks, is characterised by its extensive development and quick evolution.[92] These networks offer real-time information to users, thereby replacing conventional testing methods that necessitate specialised expertise and substantial financial investment.[93] Motion tracking, in conjunction with movement identification systems that utilise wireless devices, has demonstrated significant utility in various domains, including sports, rehabilitation, and health monitoring.[14,92–94] Studies have demonstrated a wide range of methodologies employed in the field of human activity recognition, which pertains to the automated identification of activities through the analysis of sequential observations.[95] It is crucial to comprehend that sports, particularly those at an elite level, place significant demands on individuals in comparison to the regular daily activities of common people in recreation.[14,94] Hence, the instruction of sports techniques, particularly the modification of established movement patterns among elite athletes, necessitates a nuanced approach, with feedback serving as a crucial component within this undertaking. Nevertheless, it is crucial to comprehend that sports, particularly those at an elite level, entail significantly greater demands as compared to routine daily activities.[14]

The motor skill under investigation may be influenced by various factors, including equipment and environmental limitations, particularly within laboratory settings.[58,86] Moreover, the utilisation of a marker-based optical system, which is a prevalent technology employed for motion capture, necessitates a substantial investment of time and labour, along with the expertise of skilled professionals for its operation.[36] Nevertheless, the primary concern lies in the limited capability to accurately determine parameters such as velocity and acceleration during rapid movements,[58] such as those involved in delivering punches. The presence of such evidence raises further inquiries concerning the validity of the findings and their relevance to both training and competitive contexts.

It is a demanding task to analyse joint kinematics under realistic conditions of sports performance. The reason lies in the necessity to execute techniques at the highest level, which affect data acquisition.[14,18] Sports performance is a process that depends on numerous factors causing permanent modifications and, as a result, affecting the precision of the measurement.[58] In conclusion, the system should be wireless, adaptable to any surface irrespective of the surrounding environment, ergonomic, and have adequate power and measurement characteristics.[14,18,63]

The utilisation of kinematic sensors (KS) in combat sports is subject to extra limitations, which can be seen as a contributing factor to the limited number of research studies that have employed KS in this domain. Only a small proportion, specifically 2.8%, of the total 286 papers included in the review of the application of sensors in the assessment of athletic performance in sports focused on combat sports.[18] The presence of high levels of acceleration, quick and ballistic motions, and repeated rotations of the segments of the kinetic chain are frequently observed in combat sports. However, these characteristics pose challenges for the majority of currently available sensors, rendering them ineffective in accurately capturing and measuring such movements.[12,72] When considering the impact of unit attachment position and type, as well as motor task and subject, on soft tissue,[18] the intricate nature of the topic becomes increasingly apparent.

Prior studies in the field of combat sport have examined several performance characteristics, revealing a wide range of device specifications. These include an accelerometer with an operational range spanning from 3 g to 2000 g, and a gyroscope with a range of 1000 deg to 4000 deg. As for the maximum sampling frequency, it goes up to 5000 Hz. Various research have utilised different models for the placement of sensors, employing either a single measuring device or a comprehensive full-body model.[72] The aim of this study was to suggest a specific reference frame that could offer the necessary explanatory information. Furthermore, it is imperative to take into account the alignment of the sensor-to-segment axis as a crucial aspect in the prediction of joint kinematics using wearable devices.[96] However, the acquisition of such data is feasible just under the condition that the location of the device does not exert any influence on its output.[72] In other words, it is crucial to ensure that the kinematic quantities at the designated point of attachment of the body do not beyond the dynamic limitations of the device. Additionally, it is critical that the selected place satisfy the requirements for establishing a secure attachment.

In their study, Wan Idris et al.[97] conducted a comprehensive analysis of various motion capture techniques employed in combat sports. The researchers reached the conclusion that the marker-less estimation of motion, particularly for the upper and lower limbs, presents a significant challenge. They specifically highlighted the difficulty of utilising a single computing unit to effectively manage and process data from multiple sensors simultaneously. Therefore, the current study introduces a fresh methodology as a potential alternative to conventional optical motion capture techniques, as well as earlier sensor-based methods. The methodology relies on the utilisation of sensors positioned strategically on predetermined locations of an athlete's physique, assessing the kinematic and temporal aspects through meticulously devised tests.[35,36] This approach facilitates a comprehensive examination of technique execution under situations that are either same or similar to those encountered during training and competition, while remaining cost-effective and user-friendly.

The aforementioned data holds significant value as feedback for elite practitioners of karate, since it allows for the recognition of individualised nuances in technique execution among fighters operating at the top level of the sport.[98,99] The examination of outstanding individuals might enhance comprehension regarding the underlying factors that contribute to their achievements.[100] Understanding that achieving high levels of mastery requires a challenging and intricate process, the acquisition of trustworthy and valid critical data throughout specific phases of execution holds significant importance. From an individual perspective, it is imperative to conduct a comprehensive examination of elite karate athletes, with a particular emphasis on the key moments during the execution of their techniques. While the authors acknowledge the importance of impact, which has been identified as the most crucial stage, there is a distinct need to examine the initial phase of punch execution. The preliminary stages leading up to impact might be regarded as developmental in nature, as they exhibit a gradual growth in kinematic variables.[35] It is a legitimate expectation that potential variations in each phase (i.e., beginning and developing) of performance have an impact on the ultimate result and the overall quality of the executed technique. Ultimately, it is this factor that defines the distinction between whether a punch will be awarded points or not.

Based on the aforementioned information, there appears to be a deficiency in understanding the following areas: (i) the examination of the developing stage of the reverse punch; (ii) the personalised approach to performance by high-level karate athletes; and (iii) suggestions pertaining to the utilisation of wearable kinematic sensors in the combat sport, i.e., karate. Hence, the primary objective of the present study was to accomplish the following: (i) acquire the pertinent parameters necessary for enhancing technique through the utilisation of specifically designed assessments; (ii) conduct a comprehensive analysis of the developmental stage of the reverse punch as a fundamental basis for designing a personalised training regimen; and (iii) suggest the specific implementation of wireless sensor devices based on the biomechanics of the punch. Therefore, we formulated the hypothesis that (i) there are differences in the kinematics during the developmental phase of the reverse punch across different modalities; and (ii) the timing of kinematic events follows a discernible pattern.

6.2. Materials and Methods

This case study involved the examination and analysis of a highly skilled karate athlete who has achieved notable success at both the European and World Championship levels. The subject, who was 24 years old, had a height of 1.85 metres, a body mass of 82 kilogrammes, and had 11 years of experience, provided written agreement. Additionally, the participant was in good health and had no injuries. The research was carried out in accordance with the ethical guidelines outlined in the Declaration of Helsinki and received approval from the Ethics Research Committee of the Faculty of Sport and Physical Education at the University of Belgrade (Project III47015, Protocol No. 484–2).

6.2.1 Variables

The process of selecting variables is informed by the understanding that emphasises the significance of acceleration and velocity as key factors in a punch,[13,34] as well as the crucial impact of the timeline of kinematic quantities on the sequential structure of the punch.[91] The kinematic and temporal variables considered to be significant for the evaluation of robotic perception were:

- HA – maximum hand acceleration, expressed in g0;
- tHAS – time for the onset of a hand acceleration;
- tHA – time for the maximum hand acceleration;
- HV – maximum hand velocity, expressed in m/s;
- tHV – time for the maximum hand velocity;
- BV – maximum body velocity, expressed in m/s;
- tBV – time for the maximum body velocity;
- tBAS – time for the onset of body acceleration;
- BRa – maximal body rotation angle, expressed in deg.

Among the kinematic variables, three were considered primary variables and one was classified as a derivative variable. The relationship between the velocity of the hand and its acceleration (a_x) was determined by employing a one-dimensional model of motion. The velocity samples were determined by calculating the acceleration (a_x) using the given equation:

$$v_h[n] = v_h[n-1] + Ts\, g_0\, a_x[n]$$

where v_h represents hand velocity, n denotes the sample number, T_s is the sampling interval, g_0 represents the acceleration due to gravity (9.81 (m/s^2) and a_x represents hand acceleration (m/s^2).

Temporal variables can be defined as the temporal counterparts or equivalents of kinematic events. The presence of these events aligns with the optimal temporal organisation within the kinetic chain and occupies a distinct position within the interconnected series of occurrences.

6.2.2 Procedure

Following the preliminary warm-up session, the participant was verbally instructed and demonstrated how to perform the test. The participant received instructions to execute a RP with their dominant hand, targeting the body, at a time interval of roughly 5 seconds following the auditory cue. In two separate trials, a series of three consecutive punches were executed, allowing for sufficient intervals of rest between each punch. The participant exhibited right-handedness, thereby adopting one of the two initial postures: the basic stance known as *zenkutsu-dachi* or the combat stance, referred to as *fudo dachi*. In both cases, the initial position was left. Both positions were identified as front stances due to the redistribution of body weight towards the front leg, accompanied by a flexed knee squarely aligned with the ankle of the front foot. The stances' length was roughly equivalent to two shoulder widths, with *fudo-dachi* being somewhat shorter. Additionally, the stances had a width of around one shoulder width. The efficacy of the punch was evaluated across a comprehensive range of 10 performance modalities. In addition to the initial tests, namely RPNH (hip rotation excluded from RP execution) and RPH (hip rotation included in RP), the other four tests were carried out under two primary conditions: static (S) and dynamic (D) beginning positions:

- RPSM: sliding motion preceding RP;
- RPSMO: sliding motion preceding RP, with opponent as a target;
- RPSMP: sliding motion preceding RP, with partner holding chest punch pad;
- RPSMR: sliding motion preceding RP executed on a visual signal.

In order to maintain a high level of performance in terms of scoring, encompassing factors such as proper form, sportsmanship, intense effort, situational awareness, precise timing, and accurate distance,[25] the testing procedure was overseen by three referees of exceptional expertise and international standing. The investigation focused exclusively on punches that adhered to the standards outlined in the competition rules.

6.2.3 Experimental Set-Up

In this investigation, two kinetic sensors were employed, with one attached to the hand and the other linked to the torso (see Figure 6.1). The integration of WiFi communication modules into the sensors of microcontrollers facilitated the acquisition of KS data and their transmission to a distinct LabVIEW for Loops programme operating on a laptop. The data collected from wearable devices were processed by the primary programme loop. The experimental protocol was carefully regulated and executed in intervals of 5 milliseconds. Communication was established with the User Datagram Protocol (UDP) across a heavily utilised Industrial, Scientific, and Medical (ISM) band. Due to the potential for data loss associated with packet diversity, error correcting mechanisms were implemented to replace any potentially lost samples with previously recorded values. Monitoring of the channel's quality provided conclusive evidence regarding the validity of the results.

Figure 6.1. The experimental equipment consisted of a pair of cameras and a laptop that were wirelessly linked to two sensors affixed to the athlete

In order to record the tests, we used two cameras, as shown in Figure 6.1. The cameras were situated at a distance of 2 metres from the participant and were positioned in a lateral manner, both to the left and right of the athlete. These cameras were mounted on a tripod that was elevated 1.3 metres above the ground. Because of this, there was sufficient room for the task to be carried out within the camera's field of view, and every stage of its execution could be photographed. The LabVIEW application took the signals it received from a variety of sensors and synchronised them with the signal from the video camera. It then logged all of this information into files for subsequent processing. This kind of method provides advantages over sensor-only applications, such as the ability to combine images from two cameras that are positioned at separate views; recognising human action in a more complete manner; enabling the identification and differentiation of the many stages of a movement; and recognising human action in real time.

The primary benefit of the employed methodology is in its ability to integrate diverse sources and include heterogeneous information, including pictures and inertial data. In order to enhance the accuracy of the information, a combination of four data modalities was employed, all of which were synchronised temporally. The implemented approach effectively mitigated uncertainty surrounding the acquired data, while also offering a comprehensive examination of the methodology employed. The synchronisation of the initiation and termination of a motion was accomplished by employing time stamps, as a result of the disparity between the frame per second (FPS) of the cameras and the sampling rate of the sensors. This form of synchronisation facilitated a precise evaluation of the constant time delay between the camera and the sensor devices. The data for each technique modality and trial were recorded and saved in two video files, one in .avi format and the other in .MP4 format. The data from the inertial sensors were recorded and saved as .tdms files using the LabVIEW software tool.

6.2.4 Sensor Positioning

To the best of our understanding, there is a lack of thorough research that provides specific recommendations on the utilisation of wearable kinematic sensors for testing purposes in the field of karate. Hence, various considerations were taken into consideration with regards to the placement of the sensors prior to the determination of their final positions: (i) the sequential pattern of bodily movement; (ii) the elimination of factors that could interfere with sensor functionality and connectivity; (iii) the prevention of any adverse impact on an athlete's performance; and (iv) the selection of a cost-effective and budget-friendly solution. Naturally, the primary inquiry was posed: which position would yield the most gratifying data? The choice was made by considering biomechanical facts and empirical knowledge, which encompassed:

Kinetic chain – The kinetic chain is a conceptual framework that illustrates the interconnectedness of many body parts during a punching motion. This includes the ankle of the back leg, knee, hip, shoulder, elbow, and wrist of the punching fist (see Figure 6.2).[4,13] The sequential movement of the lower limb is linked to the sequential movement of the upper limb by the rotation of the pelvis, which encompasses the entire body. Hence, the centre of gravity point located on the torso serves as the last point of reference including all pertinent kinetic and associated temporal occurrences inside the lowest segment of the kinetic chain.

The location with the highest level of optimality for obtaining the most representative data – The primary objective of the proposed methodology is to obtain the most precise data by employing a straightforward approach. This involves strategically positioning a minimal number of sensors at the most informative locations, specifically targeting the final optimal point in the kinetic chain for both the upper and lower extremities of the body. The preferred choice for the upper limb, due to evident factors, is the fist. Regarding the lower contributor to the punch, it represents the centre of gravity. The aforementioned causes are elucidated.

A technique that is devoid of any external disturbance – In order to optimise performance, it is imperative for the athlete to experience a state of uninterrupted focus and freedom from any form of disturbance.[101] In essence, conducting field research under realistic conditions is only meaningful if every aspect of its implementation aligns with the typical training and/or performance context. To accomplish this objective, it was imperative to scientifically ascertain the suitable placement of sensors and get input from the athletes. The selected venue offered an environment where wearable technological devices did not impede the athletes.

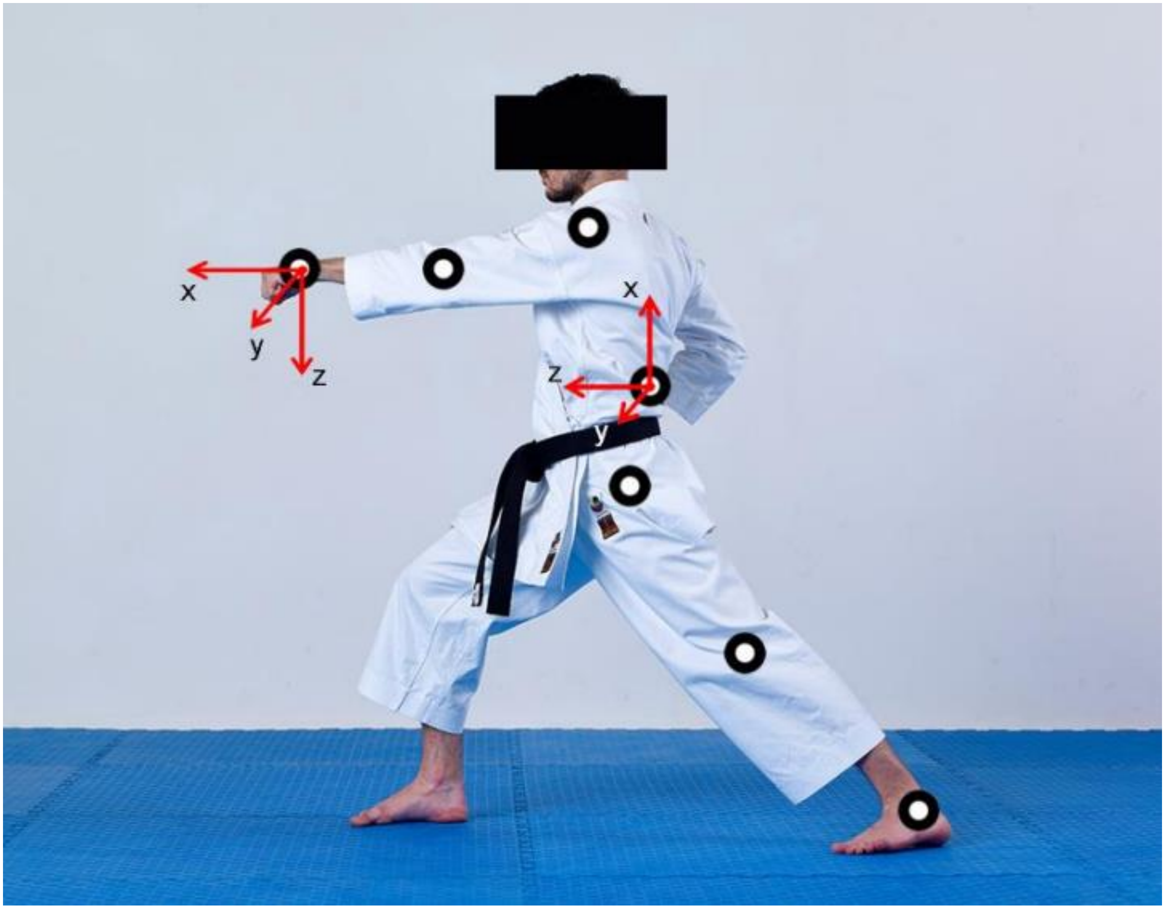


Figure 6.2. The kinetic chain involved in executing a reverse punch and the positioning of the sensors

Sensor output – The positioning of sensors should not have any impact on the output of the sensors.[72] No issues were encountered during the test trials conducted at the selected site. The kinematic quantities measured at the chosen attachment location of the body did not surpass the dynamic ranges of the sensors.

Fixation - The position of the sensor has to be optimal for secure attachment and should be able to guarantee fixation even while the explosive movement is taking place. These requirements could be satisfied by utilising an appropriate fastening kit in conjunction with the most advantageous sensor placement. Because of the use of a waist belt with a pouch that fit snugly and a glove, it was possible to position the sensors securely and achieve a higher level of output production from the sensors.[74] The particular fastening kit was selected not only for reasons of secure attachment, but also because it enabled the sensors to be kept out of direct contact with the athlete's skin while the tests were being performed (i.e., they were not subjected to the effects of an increased body temperature or sweat).

After a great deal of consideration, the exact locations of the sensors that were used to measure the kinematic parameters of GTC were determined to be as follows: (a) between the second and third lumbar vertebrae, on the back of the athlete; and (b) on a dorsal side of the punching fist within the second and fourth osseous metacarpals. Both of these locations can be found in Figure 6.2. Before conducting any tests, the conventional approach to eliminating bias was implemented in the field with the intention of preserving the accuracy of the devices. The typical interval between bias measurements was ten seconds. In the laboratory, the sensors were given a proper calibration.

6.2.5 Data Processing and Analysis

Accelerometer signals coming from wearable sensors attached to the body and hand were used to evaluate the athlete's performance in terms of their technical ability. Additionally, the quality of the technique was assessed using gyroscope signals from the KS attached to the body. In this sense, the analysis included: the principal aspect of hand acceleration in frontal movement; the absolute hand acceleration; the linear acceleration of the body; the absolute linear acceleration of the body; the rotation angle of the body in the dominant axis of movement; the rotation angle of the hand in the dominant axis of movement; the hand velocity originated from the principal aspect of hand acceleration; and the body velocity originated from the principal aspect of body acceleration. In addition to this, the time at which the parameters occurred was taken into consideration.

As was discussed before, the punch execution can be broken down into two primary phases: before and after the impact. Within each of these phases, there are a number of sub-phases that relate to acceleration, angular speed, rotation angle, and other such factors. Through the use of the threshold-triggering approach, an abrupt change in acceleration in relation to time was determined. The value of the hand acceleration threshold was determined to be 15 g_0 on the basis of the empirical data. Due to the fact that an unfiltered absolute hand acceleration signal was employed, the analysis of the events that matched in time must take into account the delay caused by the filtering process.

The data underwent post-processing and analysis with the MathCAD 7 numerical computation software. The signal analysis was conducted by applying a Butterworth filter of 5th order, namely a low-pass filter, with a cut-off frequency of 40 Hz. To mitigate the occurrence of erroneous event detection, distinct thresholds were employed for both acceleration and rotational velocity. The upper threshold value was 5%.[36,102] The initial stage in determining the factors that define technical performance involved the manipulation of signals at the reference moment of analysis, which corresponds to an impact event. The analysis of the signal was conducted within a time window consisting of 120 samples, including a time period of 0.6 seconds.

6.2.6 Statistics

Descriptive statistics (MEAN ± SD) is used to represent data. The data were computed via Microsoft Excel software designed for the Windows .10 operating system.

6.3 Results and Discussion

The knowledge gap about the RP in the phase of arising kinematic and temporal quantities was the focus of this case study. The individual technique in the investigation was carried out by means of ten distinct tests in addition to the use of sensors. The most important discovery made by the research was the change in the observed quantities. Proof of this change can be observed in the findings of the test modality (Table 6.1, Figure 6.3). Even though the emergence of the kinematic event occurred at a different point in time for each modality, it is clear that the structure of the timeline remained essentially unchanged. The highest hand velocity (HV) was recorded as the final event in the time sequence that was seen. In addition, the shortest amount of time that transpired between the beginning of hand acceleration (HA) and the maximum acceleration was observed in tests where the velocity value of the reverse punch was the lowest.

Table 6.1. Temporal and kinematic parameters of the hand and body throughout all ten test modalities, expressed as means and standard deviations

Test	tHAS (ms)	tHA (ms)	tHV (ms)	tBAS (ms)	tBV (ms)	HA (g0)	BRa (deg)
sRPNH	−120.83 ± 25.58	−60.83 ± 9.17	−20.83 ± 9.70	−135.83 ± 38.00	−61.67 ± 59.47	5.00 ± 0.23	14.65 ± 2.66
sRPH	−198.33 ± 9.31	−56.67 ± 7.53	−12.50 ± 4.18	−175.00 ± 22.14	−45.83 ± 7.36	5.39 ± 0.77	91.61 ± 1.47
sRPSM	−240.00 ± 18.97	−61.67 ± 6.83	−16.67 ± 6.06	−188.33 ± 16.33	−58.33 ± 4.08	6.09 ± 0.64	69.51 ± 10.08
sRPSMO	−235.83 ± 24.98	−73.33 ± 33.27	−25.83 ± 8.61	−186.67 ± 11.69	−60.00 ± 11.83	3.80 ± 0.71	50.09 ± 10.22
sRPSMP	−249.17 ± 8.61	−56.67 ± 6.06	−15.83 ± 4.92	−173.33 ± 11.69	−45.00 ± 7.75	7.35 ± 0.47	61.24 ± 1.59
sRPSMR	−245.00 ± 31.94	−80.00 ± 32.71	−29.17 ± 10.68	−143.33 ± 39.83	23.33 ± 40.33	4.69 ± 0.66	53.32 ± 4.10
dRPSM	−214.17 ± 12.01	−54.17 ± 3.76	−18.33 ± 2.58	−168.33 ± 82.02	39.17 ± 38.13	6.85 ± 0.50	65.27 ± 3.74
dRPSMO	−225.83 ± 19.60	−51.67 ± 2.58	−18.33 ± 4.08	−179.17 ± 75.33	−2.50 ± 12.14	6.10 ± 0.10	66.82 ± 4.03
dRPSMP	−226.67 ± 36.01	−75.00 ± 29.66	0.83 ± 28.18	−118.33 ± 29.94	10.00 ± 33.76	6.99 ± 1.23	72.89 ± 7.85

Note: RPNH – hip rotation excluded from RP execution; RPH – hip rotation included in RP; RPSM – sliding motion preceding RP; RPSMO – sliding motion preceding RP, with opponent as a target; RPSMP – sliding motion preceding RP, with partner holding punch pad; RPSMR – sliding motion preceding RP executed on a visual signal; s – static; d – dynamic

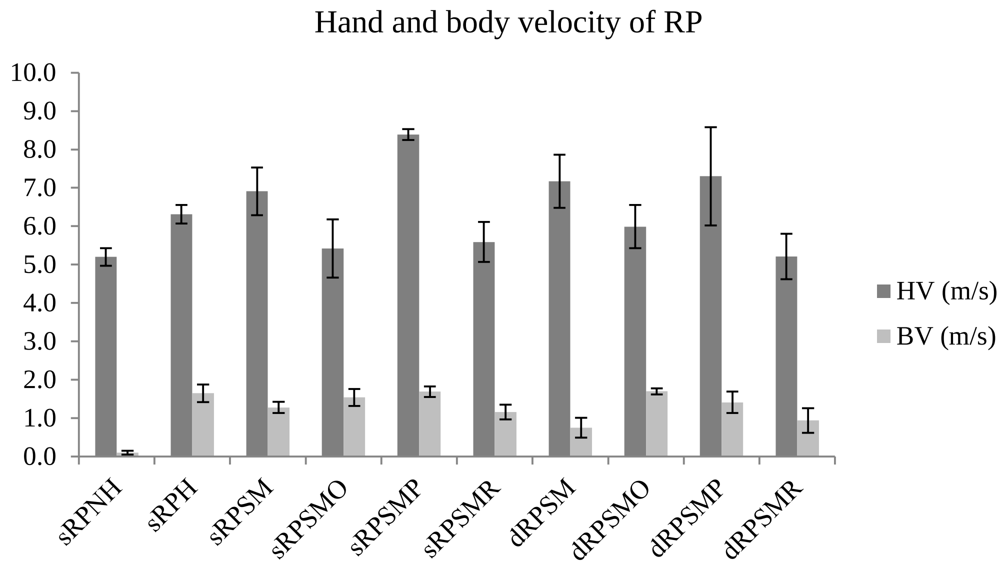


Figure 6.3. Variation in the maximal velocity (m/s) of the body and hand between the ten different reverse punch test modalities

The tests sRPNH and sRPH, provide an explanation of the fundamental requirements for technical performance and the capability of the karate fighter to apply them effectively. A smooth hip rotation that allows for proper energy transfer and accurate technique form is one of the primary needs for a good stance, in addition to stability being one of the most important qualities.[39] The study substantiated that the measured variables exhibited an upward trend, ultimately exerting an impact on hand velocity. Testing particular motor functions of karate athletes is done primarily with the intention of determining the factors that contribute to variances in technique. The results of the two tests point to a distinct shift in the athlete's performance consistency in relation to time. The investigation of the amount to which the timeline remains inflexible is intriguing, as it is expected that an athlete's adaptability will likely lead to the attainment of the optimal value of acceleration or velocity. The utilisation of sensor devices revealed temporal discrepancies in the examination procedures. The results align with prior research[35] and suggest that the sensors possess sufficient sensitivity to detect alterations in movement patterns caused by variations in the complexity of the tasks being performed. When a punch is performed in a manner that deviates from the intended model, the outcomes indicate a shift in the positions of tHV and tBV in the timeframe. The measurement of wearables' properties has significant importance due to the potential detection of these differences, which are often measured in milliseconds. This detection is made possible through the precise placement of sensors.

A similar trend is detected in the subsequent tests, albeit with varying degrees. To gain a comprehensive understanding of the intricacy of the problem and appropriately interpret the findings, it is imperative to collectively examine the set of static tests, namely sRPSM, sRPSMO, sRPSMP, and sRPSMR. While these modalities demonstrate a logical progression from earlier ones and illustrate the increasing complexity of combat scenarios in terms of training and competition, they suggest that HA and HV values do not have to necessarily rise. This aligns with prior research.[5,13,91] When executing a punch in mid-air or on a punching pad, the karate athlete achieves peak HA and HV of the highest values. In contrast, it is evident that there is a noticeable decrease in hand acceleration and velocity during the early stage of the punch when the athlete is performing the punch with the intention of scoring a point on the opponent or when the execution is dependent on a visual signal. The rationale behind these outcomes might be attributed to the test administration, which entails a specific orientation towards achieving certain goals. The tests of sRPSM and sRPSMP aim to imitate the training conditions in which the presence of a direct threat from an opponent is effectively eliminated. However, the observable disparity in kinematic parameters provides support for the execution of RP on the punching pad. The results of the dynamic testing reveal a consistent repetition of the same pattern. This assertion is substantiated by prior research that indicates that modifying the parameters of execution can have an impact on an athlete's performance.[13,91,103,104] Previous studies have demonstrated that altering the distance or targeting a higher impact has an impact on acceleration,[13,91] and our findings align with this existing body of research.

In contrast to the results obtained in prior tests, the kinematic values observed in tests sRPSMO and sRPSMR exhibit a decrease. This can be attributed to the fact that these tests aim to replicate authentic combat scenarios and the act of engaging with an opponent to a certain extent.[104] Indeed, it is accurate to assert that the adversary's behaviour lacks any form of menace. However, it is reasonable to presume that such a context elicits the activation of acquired patterns of performance. These patterns encompass the deliberate application of force in a regulated manner towards an opponent, together with the cognitive attributes of vigilance and foresight in anticipation of a possible response from that opponent. Considering the previous research,[13] it is prudent to approach these findings with caution. However, it can be inferred that applied modalities prioritize speed at the expense of high impact. The dynamic tests exhibited a consistent objective: the athlete attained greater HA and HV in the conditions of dRPSM and dRPSMP compared to dRPSMO and dRPSMR. It is noteworthy that body kinematics may not invariably adhere to this particular pattern. Furthermore, it was anticipated that the outcomes of the dynamic test would demonstrate a rise in HA and HV, however, this was not observed uniformly across all instances. In relation to the HA, this particular purpose is evident across all tests, with the exception of dRPSMP, wherein the attained value exhibited a reduction of 0.39 g_0 and the velocity of the punch was reported to be slower by 1.09 m/s. The likely reason for such a result can be attributed to a confluence of factors, namely the interplay between training regimens and actual combat circumstances. The identification of the lowest HA and HV in the RPSMR test, irrespective of the starting position being static or dynamic, is to be expected. The examination possesses a very intricate framework and necessitates the combatant to exhibit a heightened level of focus on their adversary, while concurrently predicting and responding to their actions. The test conducted under the given settings can be seen as a task amalgamation, encompassing both the athlete's anticipation and reaction. Several research have raised questions regarding the significance of reaction time in the context of karate.[50,51,60,105,106] However, it is worth noting that no previous investigations have explored the kinematic and temporal dimensions of response preparation under the specific conditions described in this study. The findings validate that the preferred temporal sequence of kinematic events is attained under situations with lower variability, namely in the static test. This timeline indicates the temporal proximity of the events to the impact, whether it is tHA, tBV, or tHV.[91]

Limitations of the Study

The primary objective of our study was to evaluate the developmental stage of RP across various punch modalities conducted by a highly skilled athlete. However, examining the kinematic and temporal characteristics of impact could offer further valuable insights and contribute to a deeper understanding of RP. While examining exceptional individuals yields useful insights into crucial technical aspects and enhances our comprehension of the intricacies behind achieving achievement, future study should encompass a broader and more diverse sample in order to draw more comprehensive conclusions. Conducting an investigation into the disparities between male and female combatants, as well as variations in age or competitive proficiency, would be of considerable significance. When examining outstanding athletes, it is advisable to concentrate on a restricted set of variables and conduct a greater number of repetitions in order to ensure that the sample is representative for a more comprehensive statistical analysis. That kind of examination should primarily focus on the most representative punches, specifically those with the greatest kinematic values. In addition, a more discerning approach should also consider anthropometric measurements, physical performance or physiological profiles, and other relevant factors. In order to conduct a comprehensive analysis, it is advisable to exercise caution and discretion when determining the quantity and nature of tests to be employed. It is advisable to conduct a comparative analysis of athletes across various weight categories, while adhering to the aforementioned parameters. Alternatively, a more extensive examination could centre on a broader range of variables, placing emphasis on the investigation of the correlation between kinematic quantities and their potential impact on the execution of the punch. Lastly, the impact should also be examined.

6.4 Conclusion

The present case study offers a comprehensive analysis of a highly skilled karate athlete, highlighting the importance of adopting a personalised strategy when addressing training and competition matters within the realm of elite combat sports. The data that was gathered has provided confirmation of the observed alterations in the kinematic parameters during the conducted tests. The acceleration values and velocity of a punch exhibited variations, indicating the athlete's adaptability to the precise parameters of the testing. The RPSMP obtained the highest HA and HV results in both the static and dynamic tests. Irrespective of the test employed, the temporal structure of the punch remained reasonably consistent. This suggests that the consistent order of kinematic events can be used to predict how well an athlete will do in the future. However, variations in HA and HV indicate distinct approaches to executing punches, likely influenced by the specific characteristics of the target. The findings given in this study provide a rationale for the necessity of conducting targeted testing and employing sensor technology in the process of data collecting. The proposed methodology is grounded in the biomechanical and practical expertise pertaining to karate combat. It takes into account various crucial aspects of executing a punch, including: (i) the utilisation of the kinetic chain; (ii) the specific starting position employed; (iii) the type of stance adopted; (iv) the distance between the individuals involved; (v) the intended target; (vi) the visual cues observed; and (vii) the level of complexity associated with the performance. Moreover, the research showcased a cost-effective and user-friendly technique that utilises merely two sensors in real-world scenarios, thereby addressing the constraints associated with a conventional laboratory methodology. Consequently, this strategy minimises the time and resources required for preparation, testing, and logistical arrangements. The data acquired in this study provides a comprehensive description of the performance of the technique, offering significant insights for enhancing practise in various training and combat scenarios.

6.5 Patents

The fundamental concept underlying the proposed testing approach is predicated on the notion that variations in technical complexity will result in alterations to kinematic parameters. In other words, the incorporation of a greater quantity of body segments will have an impact on both acceleration and velocity, specifically in relation to the performance of the RP. To date, studies have yielded sufficient empirical support to posit that the engagement with a particular activity or objective[5,13,50,91] can really influence the relevant parameters of interest. From a biomechanical perspective, there is an observed rise in complexity from the RPNH to the RPSMR, which is subsequently followed by the appropriate starting position. The proposed system demonstrates reliability, ergonomic design, optimality, and ease of use in a practical setting, thanks to the thoughtful positioning of sensors.

The tests were conducted in compliance with multiple conditions and two initial stances. A static position denotes that the athlete maintained a stationary posture, with their feet securely planted on the ground in one of the two basic stances. The athlete possessed the autonomy to select the distance and assume the starting position at their discretion, once they deemed themselves prepared. However, once established, the athlete should refrain from making any further movements beyond those specified by the test conditions. The concept of the dynamic position suggests that when an athlete assumes the *fudo-dachi* stance, they possess the freedom to engage in movements that are typical of combat in a sporting context. In a single trial, a sequence of three consecutive punches is executed. The rationale behind this phenomenon can be attributed to the imperative of athletes to swiftly adjust and acclimatise. Consequently, athletes frequently engage in a series of uninterrupted and temporally constrained manoeuvres including single or multiple strikes.[27] The trial is considered valid if all three punches satisfy the scoring criteria. There is a likelihood that certain executed RP may not reach their optimal level of effectiveness. However, it is crucial to consider these factors as they provide evidence supporting a fighter's capacity to make informed decisions and effectively employ techniques within the limitations of a fight. The tests that have been suggested are:

1. RPNH (reverse punch, no hip included): The basic stance assumed during the first test is known as *zenkutsu-dachi*. In order to achieve ZD, it is necessary to straighten the rear leg and align both hips at a 90-degree angle with respect to the direction of the stance. The anatomical alignment of the hips in question is commonly referred to as a front position. This particular configuration effectively excludes the down part of punch contributor from actively engaging in and exerting an impact on the execution of the RP. The left arm is positioned in close proximity to the torso to minimise extraneous motion that could potentially interfere with the coordinated movement of the opposing arm, thereby impacting the punch's acceleration. The right arm's elbow is flexed at a 90-degree angle and is positioned in contact with the torso. The punch is performed in a non-contact manner.

2. RPH (reverse punch, hip included): In the test modalities 2-10, the beginning stance is *fudo-dachi*. In the context of FD, it is observed that both lower limbs are flexed at the knee joint, while the hips are oriented at an angle with respect to the direction of the stance. In the realm of karate, this particular hip orientation is commonly denoted as an open position. Both upper limbs are positioned in a state of preparedness for combat, commonly referred to as the guard position. The specific configuration enables the incorporation of the complete kinetic chain during the execution of the punch. The concept behind RPH suggests that athletes engage in a performance technique including rotational movement of the hips while maintaining a fixed stance. The punch is performed in a non-contact manner.

3. RPSM (reverse punch in motion): During the third test, the RP is executed in motion. The motion that has been adopted is a combination of the usual pattern motion and the reverse punch.[27] The execution of the punch involves the leading leg advancing during the initiation of the movement and subsequently retracting upon completion. By employing this method, the trajectory of the punch execution is extended. The punch is performed in a targetless environment, without any designated marker indicating the distance.

4. RPSMO (reverse punch in motion against an opponent): This modality extends upon the previously established experimental circumstances of static position and sliding motion, by introducing an opponent as the target. The athlete is required to modify the distance relative to the target and execute deliberate excessive contact with the opponent's body. The opponent remains in static position within the fighting domain, assuming a stance indicative of preparedness for combat. Following the execution of the punch, the athlete proceeds to slip back to their original position.

5. RPSMP (reverse punch in motion against the chest punching pad): One distinguishing factor between the present test and RPSMO lies in the nature of the target being assessed. During the experiment, the opponent remains stationary in a fixed defensive position, maintaining a punching pad designed for chest punches. This particular form of target facilitates an abundance of contact and a lack of control. The participant is obligated to revert back to the initial position subsequent to executing the punch.

6. RPSMR (reverse punch in motion as a reaction to a visual signal): The final test using a stationary posture and preceding the RP entails the inclusion of an opponent. In contrast to prior modalities, wherein the athlete would initiate a punch at their own discretion, the RPSMR protocol requires the athlete to execute a punch upon perceiving a visual cue from their opponent. The opponent is positioned in a state of preparedness for combat, standing in the frontal defensive stance. Upon reaching a state of readiness, the opponent proceeds to elevate their frontal limb in a vertical manner, serving as a visible indication. In response to the visual stimulus, the athlete performs a reactive movement pattern prior to returning to their original posture.

7–10 Tests 3–6 are also conducted from a dynamic position. The rationale for this proposition is that unrestricted mobility enables an athlete to determine the optimal distance for an offensive punch execution through requisite adaptations. A crucial need for achieving greater punch efficiency is the establishment of a dynamic beginning position, which facilitates the development of elevated ground response forces.[13,107] In the context of the dynamic test involving a target, it is defined that only the athlete executing the punch is granted the freedom to move. The opponent, regardless of their assigned position, consistently assumes a stationary posture with their feet firmly planted on the surface.

7. **Study #3** Vuković V, Umek A, Dopsaj M, Kos A, Marković S, Koropanovski N. Variability and the Correlation of Kinematic and Temporal Parameters in Different Modalities of the Reverse Punch Measured by Sensors. *Appl Sci*. 2023; 13(18):10348. https://doi.org/10.3390/app131810348

The current body of research on the role of joint mobility on punch efficiency remains limited and warrants further investigation. The aforementioned principle also holds true for the correlation between the kinematic and temporal variables of a reverse punch (RP) that ultimately governs the scoring outcome. Hence, the primary objective of this research endeavour was to assess the potential impact of excluding or including body segments on various kinematic parameters, namely acceleration, velocity, rotation angle, and timing of execution. Additionally, this study aimed at investigating the potential correlations that may exist among these aforementioned numbers.

7.1 Introduction

The distinction between a punch that is considered worthy of earning points and one that does not match the criteria might be attributed to a mere few milliseconds. In addition to the enduring modifications mandated by the karate fight[13] and various adaptive interactions between the bodily systems concerned,[6] the correlation between the kinematic and temporal aspects of movement appears to be a significant factor in achieving a favourable result. From a strictly theoretical standpoint, it is imperative to focus one's attention on the fundamental aspects of acceleration, velocity, rotation angle, and temporal factors. The temporal parameters refer to the kinematic event taking place during the typical period of the punch execution within the ideal time sequence. It means that the punch is executed in the most efficient manner possible. Research on joint kinematics has typically only been conducted in a laboratory setting.[58,96] The detection systems that are currently available are often costly, and call for experienced professionals who are familiar with how to operate them.[94,108] Apart from that, they are not mobile or usable outside the environment under strictly controlled conditions. In these kinds of environments, athletes are subjected to constraints that are not often encountered during competition or training.[94] As a consequence of this, the motor skill that is being analysed may be affected by the limitations coming from the equipment and the surroundings.[58] On the contrary, the capture of a vast amount of different data in situ utilising kinematic sensors (KS) makes it possible to analyse common sports behaviours that are happening in real time. An approach such as this one generates objective assessments, in addition to improved motion estimation.[18,35,36,109] A greater understanding of the kinematic structure of a punch would lead to a base of fresh knowledge. The new insights might lead to improvements in technique and the practices of elite athletes, and striking and throwing sports,[83] such as karate would benefit from them.

The karate these days has evolved into a widely practiced sport with two disciplines: *kata* (form of predetermined techniques) and *kumite* (sports combat). But it still maintains the core of a traditional martial arts approach that is focused on fighting.[21] Karate combat is distinguished by periods with different levels of intensity that alternate with one another. Rapid actions consist of short attacks or defensive techniques, and all together, they are characterised by a great deal of diversity.[22,26,28] The ultimate goal of karate combat is to surpass the opponent with a more effective action.[25] A karate match typically lasts for three minutes and can be either an individual or team competition.[25] Aerobic activity makes up the majority of the period.[28,110] A significant portion of karate fight time elapses in dynamic movements such as preparatory motions for offence or alteration in order to be successful in defence.[26,27] Competitors will perform scoring actions during brief intervals of anaerobic and lactate-producing exertion. In order to earn the point, the performed technique has to meet defined criteria. The action has to be applied with a high degree of intensity, speed, and appropriate timing – when it has the highest potential.[25] Both kicking and punching techniques are held to the same standard in this regard.

Techniques that include punching are fundamental to a variety of combat sports.[4] Karate is no exception. Statistically speaking punches are substantially more common in top karate competitions than kicks with overall frequency of 89.09%. In addition, 66.91% of the points can be attributed to RP, and a little over the majority are earned by targeting the body.[27] Punching effectively is a difficult task that requires a lot of effort. In order to accomplish this goal in the allotted time, it is necessary to utilise all of one's biological capabilities to their fullest potential.[5] Previous studies have concentrated their attention almost exclusively on the last stage of the RP, which is known as the impact. According to the findings, the amount of energy and power that is passed through the punch is proportional to the speed of the execution.[13] Apart from that, it was revealed that the timely involvement of body segments in a successive motion impacts punching speed.[35,36] Yet, the association of kinematic and temporal quantities in the punch structure has stayed understudied. On the basis of the latest findings, it can be argued that certain temporal structures of the punch are in accordance with a certain range of achieved speed execution. The study demonstrated that within the overall chronology of movement, the punch with the highest speed consistently exhibited earlier initiation of hand movement, and the maximum velocity of the hand was attained in closer proximity to the point of impact.[36] It is known that the execution of a punch involves multiple phases, as well as that the opposite upper limbs move at different speeds throughout the performance.[73] Research has provided evidence that the kinematic and neuromuscular activity involved in executing a punch takes place within a timeframe of 400 milliseconds, following a sequential pattern of activation from proximal to distal regions.[7] In elite athletes, the maximum wrist linear velocity attains a value of 7.3 ± 0.8 m/s.[34] Research has indicated that the level of athletes' competitive experience has a significant impact on various aspects, including perceptual and response skills, indications of neuromuscular control, and overall performance. The wrist acceleration of top karate athletes is seen to be significantly faster compared to that of sub-elite competitors. Furthermore, the ability to decelerate rapidly enhances the subtlety of the punch, rendering it less conspicuous to the adversary.[57] According to the study conducted by Saponara, it was observed that throughout the initial stage of the movement, which spanned 160 milliseconds, there was a constant increment in hand velocity from 0 to 12.5 m/s. The mean acceleration obtained in this study was approximately 78 m/s^2.[12] It is important to consider the role of the lower body in the execution of a punch.[4] In other words, the coordination of the lower limb joint sequence is interconnected with the joint sequence of the upper limb through the rotational movement of the pelvis, i.e., torso. Research has indicated that karate fighters tend to exhibit a higher degree of shoulder extension. Additionally, they possess the capability to generate elevated levels of preferred velocity in order to execute coordinated joint movements.[75] It was determined that variations in task orientations and execution conditions have an impact on the kinematics of punches. For instance, the values of acceleration vary based on the predominant orientation towards force or speed at a predetermined or individually chosen distance.[13] Altering the length of the distance have a substantial impact on the generation of force and the acceleration of a punch.[91] Due to that, the analysis of RP should be based on situations that accurately simulate both training and combat environments. In contrast, a laboratory-based approach is prevalent.

In recent times, scholars have presented a range of strategies aimed at enhancing the efficacy of combat sports training. They rely on recent developments in technology such as new non-conventional systems, computer vision posture estimation, convolutional neural networks, vision and inertial sensing systems, wearable sensor devices, etc. The main objective is to comprehend the execution of punches and create effective tools for monitoring and improving combat technique across different dimensions.[53,54,73,111] Karate kinematics are conventionally researched in controlled settings.[58,59] In the field of biomechanical examination of punching techniques, researchers commonly utilise various methods, including the force platform[5,9] and electromyography.[7,112] Another frequently utilised technique is motion capture, which involves marker-based optical technology. In certain cases, motion capture is integrated with force platforms.[5,34,41,42,97,113–116] In contrast to other solutions, force platforms lack the capability to offer data pertaining to the pre-contact movement, hence impeding the understanding of the developmental stage of the punch. Electromyography (EMG) serves as a solution to address this issue; however, it is important to note that its primary drawback is in the requirement of attaching the instrument to the athlete's body, so imposing restrictions on their range of motion. In addition to this, executing punches under dynamic circumstances is a distinct challenge due to the intricate nature of movement within authentic environments and potential interference caused by velocity or muscular dimensions. Physiological processes that exhibit greater prominence or only manifest during periods of intense exercise can potentially influence the morphology or magnitude of the related electromyographic signal. Furthermore, it is necessary to normalise electromyograms (EMGs) in order to enhance their interpretability, provide sufficient reliability, and obtain a representative assessment of muscle activity.[117] Marker-based optical systems are known for their great reliability in giving spatial location data. However, they have limitations in acquiring kinematic values.[58] Primarily, the utilisation of these equipment necessitates the implementation of regulated circumstances, a multitude of indicators, and optical devices, in conjunction with the incorporation of intricate algorithms to facilitate feedback.[97] Conversely, the dynamic nature of sports necessitates the ability to adapt to intricate motor tasks. Athletes are compelled to select their movement methods via a process of self-organization, with the aim of identifying an appropriate response within the constraints imposed.[43] The integrity of this condition is undermined within a controlled setting.[94] The utilisation of KS technology in conventional combat scenarios may offer a viable alternative, facilitating precise and non-invasive data collection.[94,108,109] Wearable sensors possess a user-friendly setup that is devoid of complex configurations, hence facilitating ease of use.[33] The selection of a device with suitable measuring properties should begin by considering the nature of punching, which is characterised by high kinematic values.[63]

As previously discussed, traditional research methods impose restrictions unfamiliar to the fighter in a competition or training environment. It is obvious that restrictions originating from instrumentation and the accompanying settings may influence the technique being studied.[58] Bearing in mind that the most important issue in high-level sport is detecting barely visible variations and finding adequate solutions, the consequences are clear: The data obtained exhibit bias due to the specific measurement conditions employed. There is an additional problem. Biomechanical study of the reverse punch has not received much systematic investigation. Restricted numbers of researches were conducted with different aims, applying diverse measurement instrumentations in specific experimental setup. Consequently, fund of results represents diversity of answers given to the unique research questions. In addition to what has already been stated, the main implications of the studies in question are: (i) the variety of subjects and comparison combinations; (ii) the different test conditions that affected the monitored kinematic parameters; (iii) the different stage in reverse punch execution or kinematic founding's; and (iv) the varying positions of the research equipment, as well as indicating the reference locations. In addition to this, it is widely recognised and understood the specific kinematic requirements that should be observed during the pointing technique at the moment of impact. However, the mechanisms by which key variables contribute to the successful execution of a punch at the very beginning remain unclear. Hence, the objective of the present research is to conduct an analysis of movement sequences, with the potential to enhance comprehension of RP pertaining to the human body. Our hypothesis posits two main points. Firstly, we propose that the kinematics of the reverse punch during the developing phase are influenced by the conditions of execution. Secondly, we suggest that there exists a correlation between the kinematic and temporal parameters of both the body and hand during the developmental period of executing RP.

The study makes several significant scientific contributions. Firstly, it introduces a new and user-friendly methodology that utilises specialised test and kinematic sensors to accurately measure the temporal and kinematic variables associated with successful punch execution. Secondly, it sheds light on the developmental phase of the punch in the context of RP. Thirdly, it offers valuable insights into the relationships between various parameters that are crucial for technique performance. Lastly, it establishes a solid foundation of knowledge that can be utilised for the training of high level karate fighters.

7.2 Materials and Methods

The researchers opted for a quasi-experimental methodology in this study to investigate real-life sporting scenarios.

7.2.1 Participants

A group of seven highly skilled male athletes, who are also members of the Serbian national team and have achieved notable success in senior European and World Championships, took part in the in-field testing. These individuals have proper medical certificates to ensure their physical well-being during the study. The investigation was carried out promptly following the conclusion of the National Cup, which is one of the two prominent events held during the season, suggesting that all participants were operating at a significant level of performance. The descriptive features of the sample were determined and are shown as the mean value ± standard deviation (SD). The average age of the participants was 20.63 ± 2.07 years. The average height was 1.86 ± 0.04 m, while the average body mass was 82.25 ± 6.69 kg. The participants had an average experience of 10.50 ± 1.60 years. The study was carried out in accordance with the ethical guidelines outlined in the Declaration of Helsinki and received approval from the Ethics Research Committee.

7.2.2 Procedure

The participants engaged in a standardised warm-up session lasting 15 minutes, which consisted of general exercises. This was followed by the practise of punching techniques with different preferences. The techniques varied in technical complexity, with the difficulty level increasing progressively from the first to the last technique. The technical intricacy of the punch is evident in the incorporation of anatomical components that enhance its effectiveness, leading to a progressive transition in the execution of the punch from a stationary to a dynamic state. This methodology emulates the training regimen utilised in karate. Typically, beginner training commences with the practise of *choko-tsuki* (ChT).[7] ChT is a variant of reverse punch that is utilised with the intention of directing the practitioner's attention towards the process of executing a task, coordinating limb movements, and timing muscle contractions. The subsequent objective within the karate curriculum involves achieving proficiency in the regulation of hip movement, a skill frequently honed through the practise of *zenkotsu-dachi*, a fundamental stance.[19] Following this initial phase, the training regimen incorporates more challenging exercises, including the execution of punches while in motion, emulating fighting scenarios within the *fudo-dachi* – stance used in combat.

Two beginning postures were employed for testing purposes, namely *zenkutsu-dachi* (as depicted in Figure 7.1a and b) and *fudo-dachi* (as illustrated in Figure 7.1c and d).

Once the participants were acquainted with the technique, they proceeded to do a test comprising of three distinct modalities of RP.

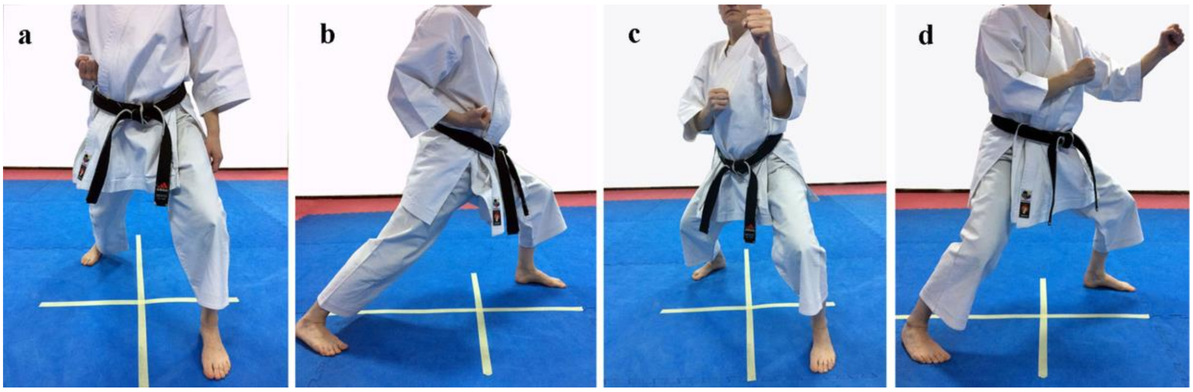


Figure 7.1. This study examines the initial stances in three modalities: (a,b) *zenkutsu-dachi* (basic stance) as observed from the front and side perspectives, and (c,d) *fudo-dachi* (fighting stance) as observed from the front and side perspectives.

1. RPNH: The execution of a punch in a static position, with the feet firmly planted on the ground and without any hip rotation, is being applied. The *zenkutsu-dachi* is the starting position, characterised by the alignment of the hips at a 90-degree angle with respect to the direction of the stance (namely, in the front position of the hips).

2. RPH: The execution of a punch in a static position, with the feet firmly planted on the ground and with hip rotation, is being applied. The *fudo-dachi* is the starting position, characterised by an angle relative to the direction of initial position (namely, open position of hips).

3. RPSM: The execution of a punch in motion which involves hip rotation. The stance and hip posture remained consistent with those seen in the second test. The motion that was implemented consisted of the common pattern motion in conjunction with the reverse punch. Hence, the test followed a specific sequence consisting of three stages: static beginning posture, sliding movement (dynamic preparation stage), and execution (dynamic execution stage). The execution step involved regaining stability in the combat stance, albeit momentarily, in a brief transitional phase.

Participants executed three straight punches from a static left position approximately five seconds after perceiving the auditory signal. Following the execution of the punch with right hand, participants proceeded to revert back to the initial posture, engaging in a repetitive sequence of three consecutive punches within the briefest possible duration. The completion of the whole action was perceived as an attempt. The rationale for this assertion is that karate fighting often encompasses temporally constrained engagements characterised by the execution of several punches in a row.[27] As a result, the athlete must quickly adapt, as seen in the test. The participants were provided with two opportunities and were allocated sufficient intervals of rest between each attempt and modality. The success of the attempt was determined based on whether all three punches satisfied the technical standards. Under such circumstances, it is probable that certain punches may exhibit diminished effectiveness or speed. However, it is imperative to consider these factors, since they contribute to a fighter's capacity to execute an effective technique within the constraints of a predetermined time frame. In order to uphold the competitors' performance at an acceptable standard, the testing procedures were overseen by three referees of esteemed status who possess extensive experience officiating at championships of the highest level.

7.2.3 Measurement and Data Processing

The movements of the trunk and limbs serve as the main source of power in various sports, enabling the execution of techniques with speed, acceleration, and control over their magnitudes.[118] As a result, the kinematic properties of the RP were determined by utilising two specially designed KS with proven reliability.[35] They were positioned as

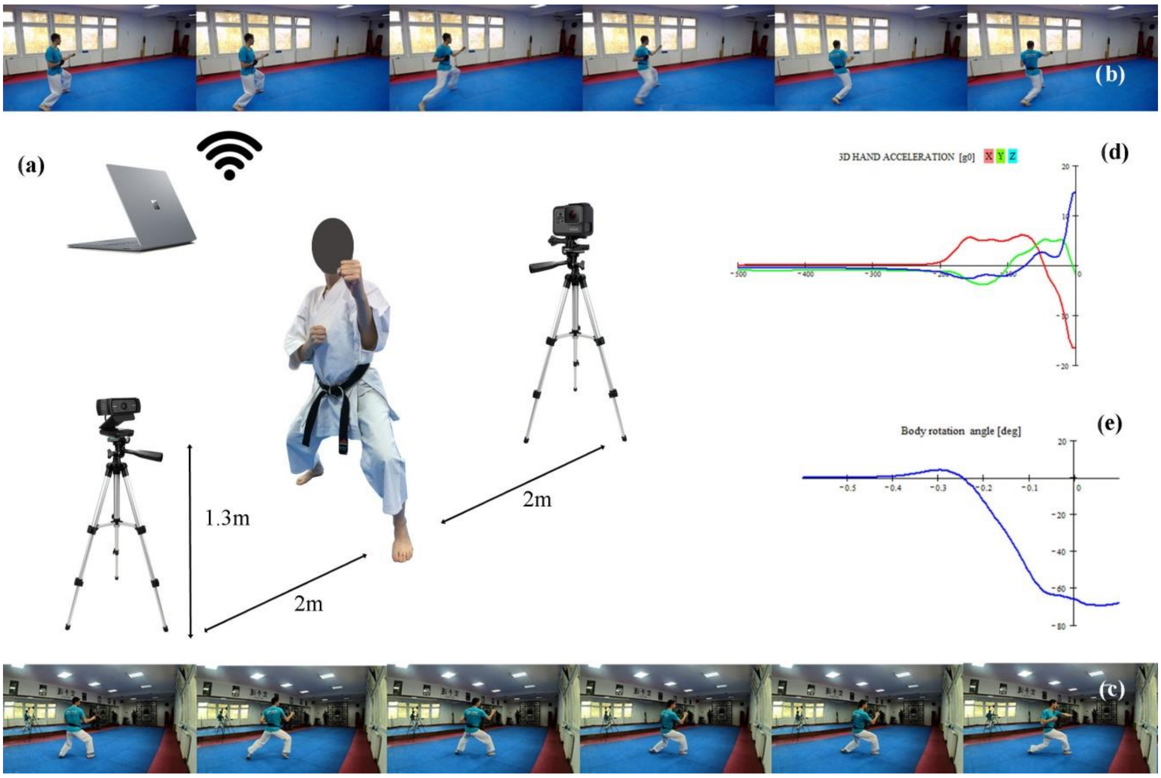


Figure 7.2. The experimental setup (a) was designed for karate testing and involved the use of multimodality data. This data included video files captured by two cameras, namely the GoPro HERO 6 (b) and Logitech C920 HD PRO (c), as well as internal data obtained from sensors placed on the hand (d) and body (e).

follows: 1) on the participant's torso, on the spot corresponding with the centre of gravity (the exact location was within the second and third lumbar vertebrae); 2) on a punching fist within the second and fourth osseous metacarpals (Figure 7.2: (a) and (b), respectively). The positioning was determined by considering the kinetic chain of technique and many elements, with the aim of minimising any potential disruptions for the kinetic sensors (KS) or the athlete, while also ensuring the collection of the data with the most explanatory potential.[17] The signal coming from KS were timed with the ones coming from video cameras. For that purpose the LabView application was used. Acquired data was saved in files on a personal computer, waiting for analysis. The 6DoF IMU sensor LSM6DS33 had buil-in absolute orientation sensor BNO055, dynamic range of accelerometer +/- 16g and, DR of gyroscope +/- 2000 dps. While the sampling frequency of KS attached to the hand was 200 Hz, the one attached to the back was lower, 100 Hz. The acquired data is read and transferred by the microcontroller using an incorporated WiFi module. This was done by the UDP protocol. The pre-impact phase of RP is distinguished by a gradual escalation in kinematic variables. In that sense, the operating range of wireless devices was adequate.

To enhance the examination process after post-processing, two cameras were employed for recording the tests: the GoPro HERO 6, manufactured by GoPro Inc. in San Mateo, CA, USA, with a frequency of 100 frames per second and a resolution of 1920 × 1080 pixels, and the Logitech C920 HD PRO, manufactured by Logitech Inc. in Lausanne, Switzerland, with a frequency of 15 frames per second and a resolution of 1280 × 820 pixels. The cameras were positioned on a tripod with a height of 1.3 metres, placed 2 metres apart from the athlete on both sides. The chosen location was deemed suitable as it satisfied two criteria: (i) providing sufficient area inside the visual range for uninterrupted task execution, and (ii) capturing the entire sequence of punch performance from its initiation to its conclusion. The possibility of conducting additional check-ups was facilitated by the integration of images captured from more than one perspective and sensor data, enabling the recognition and separation of movement phases.[119,120] The acquisition of time synchronised data from four heterogeneous devices (Figure 7.2) has been found to reduce uncertainty in the evaluation of techniques. The information was kept as video files (.avi and.MP4) as well as LabView (.tdms) files. The LabView programme received signals from two different wireless sensors. The signals coming from the sensors as well as the two cameras were recorded after they were synchronised. Post-processing and additional analysis were carried out with the numerical calculation software MathCAD 7 to complete the tasks. In order to do an analysis on the signal, a Butterworth 5th-order low-pass filter with a cut-off frequency of 40 Hz was utilised. The first step in the process of calculating the variables of interest was shifting the signals during the reference point of analysis, also known as an impact.[17,36]

7.2.4 Variables

The variables of interest in this study were selected based on their significance as key kinematic components of a punch, namely acceleration, velocity, and body rotation. The study involved measuring the highest values in the phase of punch development, while also considering the recorded time of movement beginning and the peak of the kinematic quantities on the principal axis of motion.

The temporal parameters of interest were as follows:

- tHAS – time for the onset of hand acceleration;
- tHA – time for the maximum hand acceleration;
- tHV – time for the maximum hand velocity;
- tBAS – time for the onset of body acceleration;
- tBA – time for the onset of body acceleration;
- tBV – time for the maximum body velocity;
- tBRa – time for maximal body rotation angle.

The kinematic parameters of interest were as follows:

- HA – maximum hand acceleration, expressed in g0;
- HV – maximum hand velocity, expressed in m/s;
- BA – maximum body acceleration, expressed in g0;
- BV – maximum body velocity, expressed in m/s.
- BRa – maximal body rotation angle, expressed in deg.

The primary variables in this study were BRa, HA, and BA, whereas HV and BV were calculated as integral components of hand and body acceleration. The computations were conducted using a one-dimensional movement model.

7.2.5 Statistical Analysis

During the initial processing stage, the standard descriptors (mean and standard deviation) were computed for the raw data. The assumption of normality was assessed through the application of the Shapiro-Wilk Goodness of Fit test. The study utilised the nonparametric Kruskal-Wallis test to analyse the overall variations. The subsequent stage of the analysis involved conducting pairwise comparisons using the Mann-Whitney U test, while also using the Bonferroni correction. Effect sizes (r) were computed for a specific comparison as well.[121] The final phase was the utilisation of partial rank correlation[122] with execution type as a control variable to examine potential associations between the temporal and kinematic aspects of RP. The concept of the power of correlations was established based on a study conducted by Cohen.[123] The statistical significance level was established at a probability of 95%, namely $p \leq 0.050$. The statistical analyses were conducted utilising Microsoft Office Excel 2007 and IBM SPSS Statistics, version 20.0 for Windows.

7.3 Results

Table 7.1 presents the descriptive statistics for the raw data of the kinematic and temporal quantities across the three modalities of RP.

The results of the Kruskal-Wallis test indicated statistically significant differences across all three tests for all variables, except for tBA (Table 7.2).

Subsequent examination revealed partial disparities. The analysis of Table 7.3 reveals a statistically significant variation ($p < 0.050$) in HV, BV, BA, and BRa among the three execution modalities. Notably, the effect size between RPH and RPSM was found to be the smallest. There was no evidence of significance for the HA when comparing RPH and RPSM. Statistical significance was not established for five temporal variables when comparing RPH and RPSM.

The application of partial rank correlation was conducted in the last phase, and the outcomes of the analysis are displayed in Table 7.4. A large correlation was established between tHV:tHA, BA:tBA, tBV:tBA, and BRa:BV, accounting for 57%, 36%, 34%, and 30% of the variation, respectively. The medium correlation coefficients for 17 pairs of variables were calculated.

Table 7.1. Descriptive statistics for variables of interest acquired in three tests

Variable/Test	RPNH	RPH	RPSM
tHAS (ms)	–155.89 ± 28.98	–207.89 ± 42.97	–242.38 ± 39.37
tHA (ms)	–89.89 ± 23.44	–79.44 ± 27.88	–83.21 ± 32.53
tHV (ms)	–40.56 ± 15.71	–33.33 ± 13.01	–32.50 ± 12.01
tBAS (ms)	–138.11 ± 48.21	–211.33 ± 37.88	–228.21 ± 53.13
tBA (ms)	–309.89 ± 201.28	–196.11 ± 25.96	–254.17 ± 125.06
tBV (ms)	–87.78 ± 64.21	–44.22 ± 36.49	–55.00 ± 38.62
tBRa (ms)	–15.22 ± 35.72	38.78 ± 39.77	29.29 ± 50.64
HA (g0)	5.92 ± 1.64	6.73 ± 1.22	6.48 ± 1.05
HV (m/s)	3.89 ± 0.90	6.20 ± 0.70	6.58 ± 0.64
BA (g0)	0.21 ± 0.34	0.51 ± 0.25	0.31 ± 0.21
BV (m/s)	0.10 ± 0.10	0.97 ± 0.41	1.18 ± 0.20
BRa (deg)	14.35 ± 4.96	74.95 ± 15.02	64.76 ± 13.93

Abbreviations: RPNH – reverse punch no hip included; RPH – reverse punch hip included; RPSM – reverse punch in motion; t – time of event; H – hand; B – body; A – acceleration in the dominant axis of motion; V – velocity; Ra – rotation angle; S – start.

Table 7.2. The general differences in the quantities of interest in the RP examined across the three tests

	tHAS	tHA	tHV	tBAS	tBA	tBV
Chi–Square	73.64	9.44	6.51	57.60	5.78	20.04
df	2	2	2	2	2	2
Asymptotic Significance	0.000	0.009	0.039	0.000	0.056	0.000
	tBRa	HA	HV	BA	BV	BRa
Chi–Square	38.91	12.49	87.21	37.59	95.02	91.12
df	2	2	2	2	2	2
Asymptotic Significance	0.000	0.002	0.000	0.000	0.000	0.000

Abbreviations: t – time of an event; H – hand; B – body; A – acceleration in the dominant axis of motion; V – velocity; Ra – rotation angle; S – start.

Table 7.3. The pairwise comparison and the effect size of the variables of interest in relation to the test

Test		tHAS (ms)	tHA (ms)	tHV (ms)	tBAS (ms)	tBA (ms)	tBV (ms)
RPNH	U	290.00	677.00	759.50	231.00	827.00	511.00
vs	Sig.	0.000	0.007	0.040	0.000	0.134	0.000
RPH	r	–0.615	–0.286	–0.217	–0.665	–0.158	–0.427
RPNH	U	22.00	643.50	673.50	161.00	911.50	539.50
vs	Sig.	0.000	0.010	0.020	0.000	0.776	0.001
RPSM	r	–0.841	–0.276	–0.249	–0.714	–0.031	–0.370
RPH	U	478.50	919.00	912.00	789.50	632.00	794.50
vs	Sig.	0.000	0.824	0.777	0.186	0.008	0.201
RPSM	r	–0.425	–0.024	–0.030	–0.142	–0.286	–0.137
		tBRa (ms)	HA (g0)	HV (m/s)	BA (g0)	BV (m/s)	BRa (deg)
RPNH	U	265.00	622.00	40.00	328.00	1.00	0.00
vs	Sig.	0.000	0.002	0.000	0.000	0.000	0.000
RPH	r	–0.637	–0.332	–0.827	–0.582	–0.861	–0.861
RPNH	U	440.50	616.00	6.00	542.00	0.00	0.00
vs	Sig.	0.000	0.005	0.000	0.001	0.000	0.000
RPSM	r	–0.461	–0.300	–0.855	–0.367	–0.861	–0.861
RPH	U	754.00	830.00	652.00	494.00	482.00	646.00
vs	Sig.	0.104	0.329	0.013	0.000	0.000	0.011
RPSM	r	–0.174	–0.105	–0.267	–0.411	–0.422	–0.272

Abbreviations: RPNH – reverse punch no hip included; RPH – reverse punch hip included; RPSM – reverse punch in motion; t – time of an event; H – hand; B – body; A – acceleration in the dominant axis of motion; V – velocity; Ra – rotation angle; S – start.

Table 7.4. Results of partial rank correlations between the variables of interest (N = 129)

		1	2	3	4	5	6	7	8	9	10	11	12
1.	tHAS	–											
2.	tHA	0.33 **	–										
3.	tHV	0.38 **	0.76 **	–									
4.	tBAS	0.46 **	0.29 **	0.38 **	–								
5.	tBA	0.18 *	0.26 **	0.32 **	0.12	–							
6.	tBV	0.01	0.25 **	0.11	0.10	0.59 **	–						
7.	tBRa	0.10	0.13	0.09	−0.14	0.22 **	0.06	–					
8.	HA	0.31 **	0.33 **	0.25 **	0.11	0.46 **	0.18 *	0.24 **	–				
9.	HV	–0.24 **	0.27 **	0.23 **	–0.07	0.17	0.10	–0.07	0.39 **	–			
10.	BA	–0.05	0.18 *	0.19 *	–0.38 **	0.60 **	0.44 **	0.33 **	0.39 **	0.13	–		
11.	BV	–0.20 *	0.08	–0.02	–0.24 **	0.08	0.38 **	0.03	0.03	0.24 **	0.25 **	–	
12.	BRa	–0.28 **	0.19 *	0.09	–0.23 **	0.29 **	0.43 **	0.48 **	0.27 **	0.30 **	0.45 **	0.55 **	–

Abbreviations: RPNH—reverse punch no hip included; RPH—reverse punch hip included; RPSM—reverse punch in motion; t—time of an event (ms); H—hand; B—body; A—acceleration in the dominant axis of motion (g0); V—velocity (m/s); Ra—rotation angle (deg); S—start. Note: **. Correlation is statistically significant at the $p < 0.01$ level (2–tailed); *. Correlation is statistically significant at the $p < 0.05$ level (2–tailed).

7.4 Discussion

The main aim of this research was to analyse the variations in RP kinematic and temporal parameters resulting from variances in the mode of performance, as well as to explore their correlation. The primary results derived from the current investigation were as follows:

(i) The modality of execution gives rise to notable disparities in the temporal and kinematic aspects of RP.

(ii) In contrast to kinematics, the temporal parameters exhibit a proclivity for consistency in the more challenging modalities, namely RPH and RPSM.

(iii) Significant correlations were observed between the observed quantities of the body and hand.

When evaluating the findings, it is important to consider a specific set of motor, cognitive, and perceptual abilities that undergo gradual improvement through continuous training. These abilities, particularly in terms of processing speed and execution timing, are essential for achieving elite-level proficiency in karate.[71,124] The administered assessment, comprising three variations of RP, was devoid of specific tasks or objectives, instead emulating common fighting scenarios with time constraints. This compelled athletes to swiftly adjust their approach while executing a sequence of punches.

7.4.1 Differences in the Temporal and Kinematics Variables

The primary discovery in our research is that the execution modality induces significant alterations in the observed parameters of RP. Nevertheless, it is important to exercise caution and provide further information regarding the outcomes of the pairwise comparison in relation to RPH and RPSM. Regarding the seven temporal variables, it was observed that just two of them, namely tHAS and tBA, exhibited a statistically significant difference between RPH and RPSM. In contrast, it was observed that the distinction in kinematic variables was verified in all instances except for HA. The variables HV, BA, BV, and BRa exhibit a statistically significant increase from RPNH to RPSM. However, it is worth noting that the effect size is rather small for BRa, BV and HV when comparing the RPH and RPSM modalities. Some researchers have suggested that the lower body is crucial to the success of a punch[13,43] and may even influence the speed of the hand just before impact.[4] Quinzi et al.[125] found that execution conditions affect punch speed. The *gyako-tsuki,* which is the Japanese term for reverse punch, achieves a maximum velocity of 6.28 m/s when executed from a stationary position. However, when performed dynamically, the velocity climbs to 6.47 m/s. In the present investigation, the average value of the static modality RPH was determined to be 6.20 ± 0.70 m/s. Conversely, the maximum velocity achieved in the motion modality, RPSM, was found to be 6.58 ± 0.64 m/s. In contrast, the values that were found to be the lowest were those that were obtained in the static mode, with the lower section of the body being excluded: 5.92 1.64 m/s. Therefore, the incorporation of the lower extremities in RP, along with distinct testing criteria such as executing punches while stationary versus executing punches while in motion, embodies the core principle of RP execution. Consequently, the notable variations in kinematic variables observed across the three modalities in this study can be accounted for.

Nevertheless, the current investigation presents compelling findings pertaining to the acceleration of the hand along the dominant axis. There was no statistically significant difference observed in HA between RPH and RPSM. This finding demands critical examination. It's not uncommon practice in combat karate to exercise on one's own without a partner.[22] However, a significant emphasis is placed on engaging in practise sessions against an adversary, whether with or without the aid of supplementary equipment, while assuming a combat stance. Research has indicated that alterations in performance conditions or target orientation have an impact on the kinematics of the executed technique.[8,13,77,91] Various kinematic patterns can be identified in relation to actions involving kicking with and without impact.[8] Furthermore, it has been shown that athletes with greater experience employ distinct performance tactics in contrast to their less proficient counterparts.[5,34,77] In a study conducted by Loturco et al.,[13] it was found that modifying the execution conditions of a punch leads to variations in the acceleration values. Elite athletes have a tendency to generate greater impact and select a longer distance, resulting in increased acceleration when compared to situations involving a fixed distance or the desire to generate speed. Furthermore, the combination of speed and self-selected distance yields a greater acceleration compared to the combination of speed and a fixed distance. The researchers also observed that a punch executed from a substantial distance exhibited a much higher magnitude of force compared to one executed from a close proximity. The aforementioned principle can also be extended to the acceleration of the arm.[91] The unpredictable nature of the environment in which sports are performed requires adaptation of complicated motor patterns. In order for athletes to find a suitable response within these constraints, they are required to go through a process of self-organization in which they determine the movement methods they will use.[43] Aside from the importance of focusing on the end result, it is also not unimportant for the athlete to maintain a reasonable distance from either the opponent or the target. The most important thing to remember is that the distance is always calculated in relation to the target, regardless of what the target may be. In the current study, the athletes had the option of picking the distance themselves; however, they were not provided with any sort of target or explicit goal orientation, which may help to explain the findings. Also, RP was not tested while aiming a target. As a result, providing direct evidence in this area is not something that can be done. In spite of this, the absence of a statistically significant difference in HA between RPH and RPSM may have a rational explanation in light of the knowledge that has been presented. On the basis of this information, it is reasonable to believe that it is likely beneficial for the highest quality karate competitors to incorporate a variety of targets into their routine training, such as a live person, a punching bag, a wooden beam, or a pad.

The fact that athletic training is what ultimately defines the kind of motor response that an athlete has in response to a given sporting challenge raises yet another essential question about the limits to which variability can be subjected in a real-world context. Karate athletes, due to their consistent exposure to changes in the combat environment,[13,29] acquire cognitive abilities and enhance attention processes, so enabling them to allocate more time towards the organisation of motor behaviour.[126] Elite athletes demonstrate a notable proficiency in intricate neurocognitive processes, as seen by their aptitude in acquiring intricate motor skills.[127,128] Individuals that demonstrate successful implicit learning[128] may possess a heightened motor flexibility that enables them to effectively manage their skills by engaging their biological resources optimally. As a result, they are able to modify their performance in activities with rationale. It is imperative to consistently modify the training environment by varying factors such as distance, task-goal orientation, presence or absence of a partner or target, and other relevant variables.

7.4.2 The Temporal Variables' Consistency in Demanding Modalities

As was already said, the big difference in the time parameters seen between the RPNH and the two tests is due to the inclusion of the distal part of the kinetic chain during execution and the dynamic nature of the RP. The absence of a significant difference between RPH and RPSM is deserving of attention. The high level of consistency observed in the timeline alignment of these modalities may be attributed to an optimal coordination pattern.[34,127] To clarify, aside from the sliding motion, the second and third tests were executed using identical foundations. To clarify, the arm and torso exhibit exact inter-joint coordination in accordance with the defined structure[127] immediately following the athlete's adoption of the *fudo dachi* during the dynamic execution phase. This finding holds significance as it suggests that achieving the dynamic execution stage in punch performance allows for the reproduction of a consistent coordination pattern, irrespective of the preceding preparatory phase. Furthermore, this finding elucidates the lack of a substantial disparity among temporal variables examined in the research.

Karate demands precise manipulation of technique in both stationary and active scenarios, alongside a notable proficiency in swiftly executing techniques. The enhancement of these abilities is shown to occur gradually via continuous training.[55,124] Research findings have indicated that with the acquisition of expertise, there is an observed increase in the level of stability and control in motor performance.[34,129] Furthermore, it has been seen that coordinative sequences demonstrate a lower degree of variability.[34] As for the RP, this observation can be supported by the concept of timeline consistency. The significance of experience is well acknowledged when it comes to motions that rely on the involvement of multiple joints.[77] This kind of persistence is also demonstrated in coordinative motor structures.[34] Given the high level of achievements of the study's participants, it is plausible to argue that the consistency in adhering to the designated schedule serves as a legitimate indicator of the effectiveness of techniques within the broader context of a dynamic combat situation as replicated in the utilised modalities. In different terms, it can be stated that quantities such as kinematics are prone to exhibiting predictable variations, whereas their temporal occurrence tends to remain relatively constant. This supports recent studies that showed the technique's time structure differed by RP velocity.[36]

From a practical standpoint, these results indicate that effectively managing a time structure necessitates thoughtful training planning. This implies that introducing a higher degree of variability in punch execution merely through the kinetic chain may not necessarily result in any significant changes. The practise of techniques under basic settings, with an emphasis on various areas of execution, when paired with training that incorporates improvements to the overall environment, can lead to appropriate modifications. The utilisation of such a methodology could potentially lead to the preservation of the consistency of the temporal structure and the enhancement of the study of motion. Nevertheless, it is advisable to use caution.

7.4.3 Correlations between the Temporal and Kinematic Variables

The results of the research revealed that the execution of punches is mostly influenced by a positive correlation observed between the following pairs of variables: BRa:BV, tBA:tBV, tBA:BA, and tHA:tHV. This correlation accounts for around 30% to 57% of the observed variance. According to the findings of Loturco et al.,[13] a significant proportion (56-65%) of the variance in punch acceleration may be attributed to the levels of power and strength in both the upper and lower limbs. This suggests that the remaining variance is likely to be influenced by technical aspects. The main attribute of the most successful movement structures in sports that involve ballistic throwing or striking motions is a significant level of synchronisation across all body segments.[130,131] The maximisation of energy transfer efficiency via the kinetic chain is achieved through optimal timing, which involves the peak angular velocity of various body segments such as the pelvis, torso, arm, forearm, and hand, as well as precise activation of the proximal to distal segment.[131] Therefore, it can be stated that the execution of a punch is contingent upon the ideal ratio of kinematic parameters and their timely integration within the motion sequence.

The study of observed pairs of variables with large and medium levels of correlation led to the discovery of this particular line of execution. Specifically, it was shown that earlier initiation of body acceleration corresponded to an earlier attainment of maximal velocity in the punch. Furthermore, it is worth noting that the period at which the body experiences its highest acceleration will have a beneficial impact on the greatest acceleration of the hand. Moreover, the best timeframe will also coincide with the occurrence of the maximum velocity of the hand. It should also be noted that an increase in body acceleration would manifest itself at an earlier point in a chronological sequence, thereby influencing the acceleration of the hand to a greater extent. The aforementioned principle is also applicable to tHA and tHV: If the maximum hand acceleration is reached earlier in a given timeframe, the HV will be recorded earlier as well. It can be stated that the observed association between BRa:BV and BRa:tBR serves as a mechanism for lumbopelvic control, which in turn influences the execution of rotational power. According to a report, the torso plays a significant role in baseball, accounting for approximately 50% of the kinetic energy and force generated during a throwing motion.[132] It was also stated that rotational movement of the pelvis in punch execution influences arm angular velocity.[5] In order to optimise the transmission of kinetic energy during a punch, it is insufficient to only achieve a specific angle; it is important to halt the rotation of the hip with force at the precise moment.[19] Our findings substantiated this assertion.

The aforementioned results underscore the imperative need of consistently reinforcing the fundamental principles of karate in the training regimens of elite athletes, a practise that is also prevalent among beginners. The inclusion of technique execution control, appropriate muscle engagement in contraction, and timed coordination should be seen as integral components within the fundamental training regimen. This concept establishes a crucial basis for enhancing the efficacy of the procedure through a more sophisticated approach.

In conclusion, it may be argued that the correlation coefficients observed in our study are not a perfect fit for the theory that has been provided. The likely factors contributing to this evidence were the lack of goal- or task-oriented approaches and the absence of direct guidance on the execution of a punch. In essence, during the repeated performance of RP, athletes were primarily concerned with ongoing adaptation within a limited timeframe. Additionally, they were actively selecting individualised tactics to optimise their scoring capabilities.

7.4.4 Contribution of the Study

The research presented has made both theoretical and practical contributions to the current body of knowledge. The outcomes of this study can be categorised into two primary categories. The first domain encompasses the multidimensional field that combines engineering and sports-related challenges. The second domain focuses on enhancing combat sports training practices for punching techniques.

The utilisation of real-time data synchronisation, which involves the integration of multimodal sensors and camera fusion, is not widely adopted due to many limitations associated with data gathering. However, a limited perspective focused solely on the advancements in measuring devices does not necessarily result in tangible advancements in practical applications. Nevertheless, the integration of non-traditional engineering methods alongside input from sports professionals, obtained through implementation in a controlled setting, yields numerous benefits including advancements in measurement, instrumentation, and estimate techniques within the realm of sports. The reliability, usability, and affordability of innovative solutions are crucial in providing real-time input for the measurement, control, and assessment of athlete performance.

The study examines the principle of punch performance, which is applicable across several combat sports. The findings of the study extend beyond the realm of karate, specifically in relation to the developmental stage of the strike. The importance of the impact stage in the execution process is undeniable. However, the commencement of the punch, including the alteration in the curve of kinematic and temporal characteristics, elucidates the genesis of the RP. In essence, during the developmental phase of the RP, several potential deviations or desirable patterns of execution emerge and subsequently influence the effectiveness of the technique. The attainment of exceptional athletic accomplishments is contingent upon surmounting minute differentiations that are challenging to discern. Therefore, it is crucial to ensure the accuracy and precision of measurement devices that are carefully utilised within an appropriate experimental arrangement. The alteration of the punch's form across several modalities elucidates the potential impact of instructors on the enhancement of technique. The achievement of this objective is solely attained by meticulous strategic formulation of distinct training exercises that align with various objectives.

7.4.5 Limitations of the Study and Future Research

It is fair to acknowledge that the current study possesses certain limitations. Notwithstanding that the participants were highly skilled national team members and had achieved recognition at both the European and world levels, it is important to acknowledge that the sample size and gender representation can be deemed restricted. The lack of goal orientation and a specific target may have had an impact on the measured quantities. However, given the suggested modalities, it is important to see these requirements as the subsequent stage of variability, and it is recommended that the proposed test not be dismissed in further studies. In order to examine the correlations, it is advisable to do an analysis on the dataset stratified by the maximum velocity or consider solely the optimal execution from each trial. Furthermore, the omission of the last phase of the punch in the analysis hinders a thorough comprehension of the technique's efficacy. The knowledge gap pertaining to the utilisation of sensors in combat sports remains unresolved in several aspects. These include the need to compare the positioning of sensors in various locations to enhance data collection, the application of sensors with an extended operational range, the integration of force and kinematic sensors, and the simultaneous use of sensors on athletes and equipment, etc.

7.5 Conclusion

The findings of the study have substantiated that the manipulation of body segments, along with the variability in performance dynamics, have a significant impact on kinematic parameters. Significant correlations are determined between the measured quantities, both large and medium. Practically, in-situ data acquisition shows the punch's variations in key efficiency parameters. Furthermore, the use of precise assessments in conjunction with strategic placement of measuring instruments facilitates impartial evaluation, serving as a foundation for enhancements in both instructional and competitive settings. This strategy redirects the training emphasis of high-level athletes towards the specific intricacies that are common among combat sports. This phenomenon gives rise to the analysis of enhancement techniques that extend beyond the boundaries of karate as a sport.

8. Additional Considerations

8.1 Enhancing Punch Efficiency through an Individual Approach to the Technique Study

Studying exceptional individuals in sports allows researchers to address key issues as a valuable and rare sample,[133,134] giving the opportunity for in-depth and multi-faceted investigations of complex problems in the context of their everyday occurrences.[133] Of course, such an approach has its own limitations. But it also has advantages and serves to lay the groundwork and point out potential problems[133,134] so that future studies can provide more substantive findings.

The published studies discussed above do not show the totality of possibilities covered by the proposed methodology. They represent just a part of the research. Multiple case analyses of just the basic descriptive results of the participants in the study show the richness of the data and the level of personal differences captured with the KS. Of course, these kinds of results have to be discussed in an explanatory way, avoiding generalisations and suggesting possible implications in theory and practice in combat sports research methodology and training practice.

In that sense, static and dynamic test modalities are presented and analysed separately, offering a base of knowledge focused on (i) the fundamentals of karate technique and (ii) the technique's combat application, respectively.

8.2 The Static Test Modalities

The analysis of the three team fighters shows the similarities, differences, and personal patterns in the punch execution.

The basic descriptive characteristics for the karate athletes (KA) were as follows: KA_1: age, 22 years; height, 1.82 m; body mass, 76 kg; experience 11 years; KA_2: age, 24 years; height, 1.85 m; body mass, 82 kg; experience 11 years; KA_3: age, 20 years; height, 1.91 m; body mass, 92 kg; experience 8 years.

8.2.1 Results

Table 8.2.1 shows the personal signatures in the temporal parameters of the three athletes obtained in six tests. Although some similarities can be noticed in the order of the time parameters in the overall timeline structure, it seems that a certain time of appearance is what makes the difference. Such results suggest variations in kinematic structure (Figure 8.2.1) regarding HV, HA, BV, and BRa and indicate possible performance outcomes.

Table 8.2.1. Hand and body temporal parameters (MEAN ± SD) for six modalities of execution

Test	Athlet	tHAS (ms)	tHA (ms)	tHV (ms)	tBAS (ms)	tBV (ms)
RPNH	KA_1	–120.83 ± 25.58	–60.83 ± 9.17	–20.83 ± 9.70	–135.83 ± 38.00	–61.67 ± 59.47
	KA_2	–189.17 ± 13.20	–111.67 ± 35.59	–34.17 ± 15.30	–160.83 ± 16.25	–90.00 ± 41.35
	KA_3	–136.67 ± 6.06	–86.67 ± 4.08	–50.83 ± 13.20	–153.33 ± 26.58	–54.17 ± 80.46
RPH	KA_1	–198.33 ± 9.31	–56.67 ± 7.53	–12.50 ± 4.18	–175.00 ± 22.14	–45.83 ± 7.36
	KA_2	–282.50 ± 22.97	–79.17 ± 17.72	–42.50 ± 8.22	–256.67 ± 15.71	–18.33 ± 13.66
	KA_3	–179.17 ± 7.36	–68.33 ± 13.66	–28.33 ± 8.16	–169.17 ± 7.36	12.50 ± 11.29
RPSM	KA_1	–240.00 ± 18.97	–61.67 ± 6.83	–16.67 ± 6.06	–188.33 ± 16.33	–58.33 ± 4.08
	KA_2	–275.00 ± 37.15	–73.33 ± 8.16	–36.67 ± 10.80	–305.00 ± 54.77	–56.67 ± 41.07
	KA_3	–236.67 ± 35.59	–73.33 ± 9.83	–30.00 ± 10.49	–169.17 ± 21.54	4.17 ± 18.28
RPSMO	KA_1	–235.83 ± 24.98	–73.33 ± 33.27	–25.83 ± 8.61	–186.67 ± 11.69	–60.00 ± 11.83
	KA_2	–283.33 ± 5.77	–111.67 ± 50.58	–53.33 ± 5.77	–343.33 ± 37.53	–61.67 ± 76.54
	KA_3	–262.50 ± 20.43	–77.50 ± 42.87	–24.17 ± 3.76	–198.33 ± 22.51	–51.67 ± 31.09
RPSMP	KA_1	–249.17 ± 8.61	–56.67 ± 6.06	–15.83 ± 4.92	–173.33 ± 11.69	–45.00 ± 7.75
	KA_2	–298.33 ± 5.77	–66.67 ± 7.64	–18.33 ± 2.89	–233.33 ± 16.07	–3.33 ± 16.07
	KA_3	–220.00 ± 47.96	–58.33 ± 18.07	–20.00 ± 3.16	–182.50 ± 33.28	–41.67 ± 6.83
RPSMR	KA_1	–245.00 ± 31.94	–80.00 ± 32.71	–29.17 ± 10.68	–143.33 ± 39.83	23.33 ± 40.33
	KA_2	–303.00 ± 30.52	–63.67 ± 6.94	–34.00 ± 4.31	–227.33 ± 34.38	–15.67 ± 47.54
	KA_3	–272.50 ± 24.24	–115.83 ± 28.88	–15.00 ± 3.16	–148.33 ± 23.59	0.00 ± 32.56

Abbreviations: RPNH – hip rotation excluded from RP execution; RPH – hip rotation included in RP; RPSM – sliding motion preceding RP; RPSMO – sliding motion preceding RP, with opponent as a target; RPSMP – sliding motion preceding RP, with partner holding punch pad; RPSMR – sliding motion preceding RP executed on a visual signal; KA – Karate Athlete.

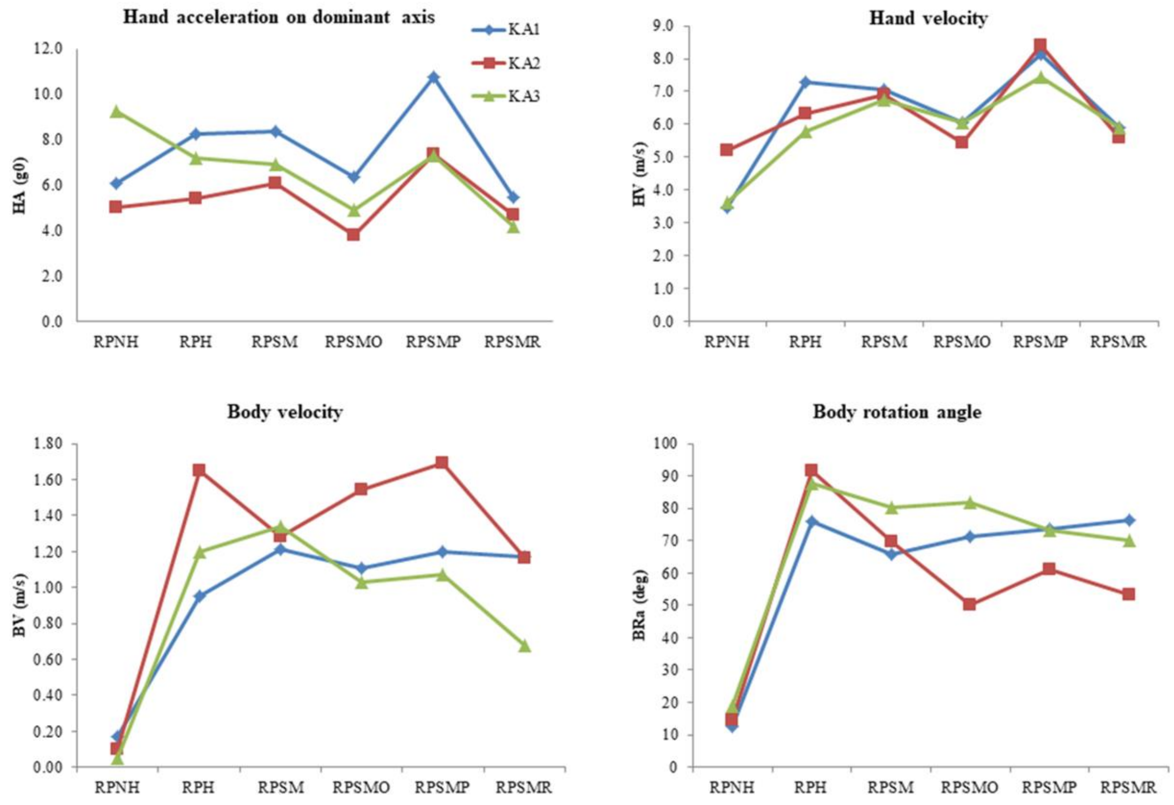


Figure 8.2.1. Change kinematic quantities over six modalities of reverse punch

Note: RPNH – hip rotation excluded from RP execution; RPH – hip rotation included in RP; RPSM – sliding motion preceding RP; RPSMO – sliding motion preceding RP, with opponent as a target; RPSMP – sliding motion preceding RP, with partner holding punch pad; RPSMR – sliding motion preceding RP executed on a visual signal; KA – Karate Athlete

8.2.2 Basic Foundation of RP

The first two tests (RPNH and RPH) can be considered as the core of the RP showing the pattern of performance when the RP is isolated from the lower part of the kinetic chain and, in opposite, when it is supported by it. Based on the results, it can be concluded that the lower part of the body affects the punch velocity and such argumentation is supported by the BV and BRa data (Table 8.2.1, Figure 8.2.1). Back to the hand velocity, it is worth to note that KA_1 reaches the highest HV as well as HA in the time point closest to the impact which is consistent with previous findings.[36] Interestingly, time elapsed between tHAS and tHA differs between athletes and achieved HA implies different tendencies in the execution. KA_1 and KA_3 in average need less time to attain HA. But, as KA_1 and KA_2 show increasing in HA in RPH, the same test conditions lead KA_3 to drop down HA. Despite that, KA_3 manages to increase the hand velocity (Figure 8.2.1). Such evidence may result in conclusion that KA_3 is the competitor with the reduced control over the ability to engage its own biological capacities in the most productive manner and make proper transfer through engaged segments. Even dough this information is a valuable starting point it can't be regarded as enough. In the final analysis body kinematics has to be taken into account. It is important to think of it not just as a supporting link in the kinetic chain,[19] but also in relation to temporal and kinematic scope for adaptation strategies in order to achieve maximum efficiency.[36] In that context, further analysis of KA_3 may provide enlighten explanation.

The main information coming from these two tests is answer to the question: whether HA and HV are increasing with inclusion of the lower part of the kinetic chain? It is usually expected to be so.[56] In practical terms, any type of aberration from the proposed pattern suggests correction training. Such training is typically founded on the practice of ChT. The main difference between performance conditions of RPNH test and basic practice of ChT lies in the fact that natural stance allows greater pelvic displacement than the basic stance in the applied test. Also, our test excluded the opposite arm from the punch execution, thus preventing the effect of upper limbs coordination to influence the punch kinematics.[19] The next level of comparison, i.e. RPH, brought in the scene these factors enabling clearer understanding of true importance of hip movement in punch execution.

The time parameters of the punches have not been studied extensively as kinematics. However, they are as useful. It has been confirmed that the peak angular speed during the internal arm rotation in ChT occurs later than the arm flexion and forearm extension.[7] The same study confirmed that group of novices tended to achieve peak angular speed of the forearm movements significantly earlier than karate experts. According to Latash (1998) the motor skill is more directly related to the trajectory of the punch focus point then to the individual trajectories of joints.[135] In the light of application of specific testing, analysing small and informative number of data and keeping the process as simple as possible, these results imply some guidelines for the interpretation of selected variables in the study. Basic testing of HA and HV can indicate if the punch is executed mainly on the dominant axis, or the athlete tends to lose the focus. Lower achieved values in the earlier point of the overall punch timeline may indicate aberrations which are less tolerable on the high competition level. This also means that the diminishing performance irregularity in the technique as well as decreasing inconsistencies in performance requires pure basic training with as less variability as possible. Athlete's individual capacity to learn implicitly[128] will determine the extent of such approach as an involvement (the time and the amount) of inconsistency conditions in training process.

8.2.3 *Kumite* Foundation of RP

Interesting findings regarding time parameters (Table 8.2.1) should be pointed out. Foremost, the tendency observed in the first two tests (the time that elapses between the beginning and the peak of acceleration) is maintained regardless of the test modality under the static execution condition. This finding indicates that an even deeper analysis can be applied and that the subject of such an analysis may be the temporal structure of the time parameters, suggesting its potential importance in the athlete's personal signature during the punch execution. KA_2 shows the least variability, as much as 6.53 %, with respect to time required to achieve maximum hand acceleration. Yet, KA_3 reaches variability of 30%. KA_1 and KA_2 achieve the highest HA and HV in the test RPSMP (Figure 8.2.1). In that particular test, time elapsing to HA was the shortest. Similar happens with the KA_3, and a comparison of the tests results of this athlete emphasise the fact that when he manages to shorten the time between tHAS and tHA, achieves the highest HA and HV.

Static tests reveal certain similar tendencies in regard to HA and HV. The lowest hand acceleration and velocity are achieved in the test requiring athletes' reaction to the opponent, and the highest when they were aiming at the punching pad. On the contrary, body kinematics shows differences in BV and BRa between athletes, indicating that some parts of the kinetic chain are less adaptive then others (Figure 8.2.1). It seems that, concerning RP, upper part of the kinetic chain is rigid to adaptive strategies, leaving the lower limbs and the body to deal with the necessary adjustments and making the personal signature more distinctive. For example, assumption about reduced control over biological capacities engagement concerning KA_3 can be supported by BV and BRa (Figure 8.2.1). It is expected that body kinematics reaches maximum values before the impact.[36,56] It is, though, hard to govern this demand in the dynamic conditions while static test design minimizes disruptive factors allowing fighters better body control. It's not enough just to push the ipsiolateral hip forward to ensure RP efficiency,[19] it is also necessary to stop hip motion sharply and tense the muscles powerfully to form the appropriate support for the transfer of energy and movement of the upper body.[7,19,37] KA_3 in more than a half of the number of tests (excluding the RPNH) fails to reach the maximum body velocity before the impact. Also, it is supposed that BV should arise after the sliding movement. Surprisingly, that is not the case with KA_3. Quite opposite, from RPSM to RPSMR, BV is obviously dropping down, reaching the lower point in compare to RPH. Aforementioned indicate the necessity for the training focusing on lumbopelvic control as a foothold for optimal biological capacities engagement, hence higher punch efficiency.

As already stated, there are differences in achieved HA and HV in regard to test modality, however regularity is also observed. When performing RP in the air or in a punching pad, athletes reach higher HA and HV. On the contrary, aiming the opponents body, regardless of whether they chose the moment to start or reacted to the opponent's visual signal, HA and HV values evidently decrease (Figure 8.2.1). It should be pointed out that no matter what was the condition – static or dynamic starting test position – main task was always the same: to perform the most efficient punch. The interpretation of efficiency may appear to depend on the performance conditions.[13] Also, significant correlations were found between RP accelerations performed in different conditions and upper and lower body power and maximal strength. Aiming to achieve given velocity, punch execution entails the acceleration of the actual mass to the impact velocity. Although the actual mass cannot be modified, different muscle groups and actions can be utilized to a greater or lesser extent to achieve the aimed acceleration.[107] Since participants in this research were not instructed to perform RP as fast, or as strong as possible, nor they were guided in relation to distance (i.e. they were not given the guidance what should be regarded as efficient), they made choice for themselves in accordance to the regular practice. Thus, different task orientations may be the reason for differences between tests and similar execution tendencies among participants.

As shown, the obtained results confirmed that different modality of kinetic chain inclusion influences RP quantities. In addition, personal signature of RP is confirmed for each analysed competitor over six modalities regardless of condition applied. Also, some similar tendencies were registered depending on the modality of performance.

8.3 The Dynamic Test Modalities

The analysis of the same competitors chosen as representative sample shows how changes the test modalities from a static to a dynamic affects punch execution in terms of application in *kumite* surroundings.

8.3.1 Results and Practical Application

Temporal parameters obtained in dynamic tests show that athletes perform RP in specific manner making them distinguished in comparison with each other (Table 8.3.1). Data also suggest certain level of similarity with respect to overall timeline structure. Despite to that, each athlete's timeline structure is different. Analysis revealed that the athletes achieved different maximum kinematic values (Figure 8.3.1). It is, also, worth to notice that level of variability changes individually and in relation to the modality of testing. It was found that each punch modality reflects in distinguished manner in relation to kinematic variables. Despite having some similar tendencies in performance, athletes execute RP in way that can be regarded as personal signature.

Table 8.3.1. Hand and body average values of temporal parameters for dynamic tests dRPSM, dRPSMO, dRPSMP, and dRPSMR

Test	Athlet	tHAS (ms)	tHA (ms)	tHV (ms)	tBAS (ms)	tBV (ms)
RPSM	KA1	–214.17 ± 12.01	–54.17 ± 3.76	–18.33 ± 2.58	–168.33 ± 82.02	39.17 ± 38.13
	KA2	–308.33 ± 47.26	–63.33 ± 2.89	–26.67 ± 5.77	–201.67 ± 20.21	–46.67 ± 82.82
	KA3	–206.67 ± 8.16	–95.83 ± 10.21	–25.00 ± 4.47	–152.50 ± 77.38	61.67 ± 4.08
RPSMO	KA1	–225.83 ± 19.60	–51.67 ± 2.58	–18.33 ± 4.08	–179.17 ± 75.33	–2.50 ± 12.14
	KA2	–323.33 ± 7.64	–58.33 ± 2.89	–33.33 ± 2.89	–221.67 ± 18.93	50.00 ± 18.03
	KA3	–233.33 ± 24.22	–79.17 ± 28.00	–22.50 ± 2.74	–200.00 ± 73.28	–21.67 ± 10.80
RPSMP	KA1	–226.67 ± 36.01	–75.00 ± 29.66	0.83 ± 28.18	–118.33 ± 29.94	10.00 ± 33.76
	KA2	–290.83 ± 26.54	–65.00 ± 0.00	–31.67 ± 9.31	–181.67 ± 26.58	33.33 ± 31.89
	KA3	–192.50 ± 68.61	–79.17 ± 30.40	–24.17 ± 3.76	–151.67 ± 52.79	–10.00 ± 20.49
RPSMR	KA1	–251.67 ± 23.63	–51.67 ± 2.89	–15.00 ± 5.00	–148.33 ± 10.41	20.00 ± 40.93
	KA2	–322.78 ± 45.90	–74.44 ± 49.59	–33.33 ± 15.00	–199.44 ± 33.30	–42.22 ± 55.40
	KA3	–305.00 ± 136.11	–100.00 ± 50.00	–30.00 ± 8.66	–181.67 ± 29.30	15.00 ± 56.79

Abbreviations: RPNH – hip rotation excluded from RP execution; RPH – hip rotation included in RP; RPSM – sliding motion preceding RP; RPSMO – sliding motion preceding RP, with opponent as a target; RPSMP – sliding motion preceding RP, with partner holding punch pad; RPSMR – sliding motion preceding RP executed on a visual signal; KA – Karate Athlete.

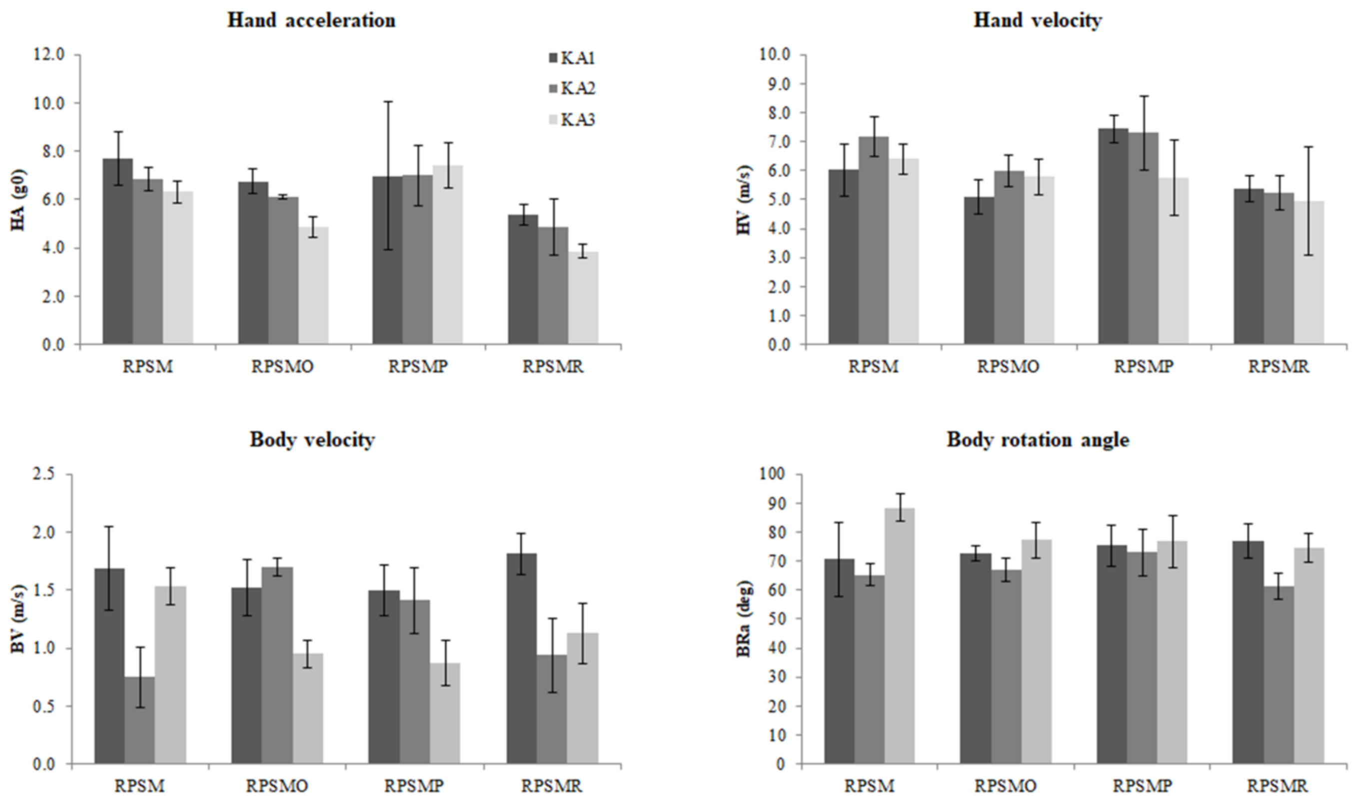


Figure 8.3.1. Change in kinematic quantities over four dynamic modalities of reverse punch.

Abbreviations: RPNH – hip rotation excluded from RP execution; RPH – hip rotation included in RP; RPSM – sliding motion preceding RP; RPSMO – sliding motion preceding RP, with opponent as a target; RPSMP – sliding motion preceding RP, with partner holding punch pad; RPSMR – sliding motion preceding RP executed on a visual signal; KA – Karate Athlete.

Persistence in the timeline structure observed through test modalities is actually rather interesting. Irrespective of the test type adopted, timeline of kinematic events stays similar. This is in accordance with previous findings[36] highlighting that the specific timeline corresponds to certain velocity. Apart of the general similarity, the tendency to persist in the same pattern is neither present nor expressed equally in all athletes. Executing sequence where linear velocity reaches maximum implies that each part of the kinetic chain is included at the greatest velocity of the preceding one.[37] In such sequence tHV is expected to be at the end of the timeline, which is not the case with the time pattern observed in the results of KA_1 and KA_3 (Table 8.3.1). Both of the athletes reach highest HV before BV (Figure 8.3.1) which follows after the impact. Conversely, KA_2 predominantly maintains the time pattern in which tBV precedes tHV. Referred findings, highlighted assumed regularity of upper part of the body and more diverse execution pattern strategies (implying possible adaptive potential) of proximal part of the kinetic chain.

Tendency to reach higher hand acceleration and hand velocity in RPSM and RPSMP in compare to other two tests is evident, but only for KA_1 and KA_2 (Figure 8.3.1). The participant KA_3 demonstrates completely opposite routine. It may seem that the more complex task is the performance of KA_3 becomes less efficient. In practical sense, this type of fighter will probably do well with similar athletes fighting with lower range of techniques, thus less variability. It should be pointed out that different approaches to the problem, but above all, targeting diverse quantities in various performance conditions make it hard to compare results of the studies.[13,103] It can be speculated that feeling no threat when performing punch in the air, and possible aiming higher force when executing RP in a punching pad, participants reach higher HA and HV. But, when being under pressure to comply the competition rules or to react to the opponent behaviour, athletes co-adapt[104] and execute punch with more caution, thus affecting kinematics. One more issue should be addressed. When an attacker strikes with a constant arm weight, the higher velocity generates the larger energy involved in the impact.[103] The highest velocity in our study was reached in the test employing punching pad.

Lastly, RPSMR (the most demanding modality of execution) test results need to be discussed. When challenged to execute a scoring technique on the opponent's reaction, athletes achieve the lowest HV values in comparison to other test modalities. Studies have mainly been dealing with the reaction time of karate athletes under the different conditions and types of stimuli.[50,51,105,106] While some authors underline the need to test the RT as an important ability affecting success in karate athletes,[51,60,105,106] opposite argumentation is also present.[50] Nevertheless, it cannot be denied that interception accounts for scores in karate matches[27] and that it is a part of a fighter’s training. In that regard the test RPSMR is sort of task amalgam combining athletes’ ability to anticipate and react as fast as possible. However, to the author’s knowledge, differences in kinematics and temporal quantities during the performance of a reaction-type task under different conditions have never been investigated. A comparative analysis of the three athletes reveals some other significant data and display potential adaptation strategies and individual differences between competitors. For example, KA_1 in RPSMR reaches almost twice the body velocity of a KA_2 in addition to larger body rotation, and it would be reasonable to expect that he will also outperform KA_2 in HV. Instead, it is vice versa. The explanation may lie in the fact that KA_2 reaches the BV in the time before impact unlike the KA_1 who makes it happen after the central event of RP execution and 62.22 ms later than KA_2.

8.4 Use of Sensor Technology in the Analysis of Punch Kinematics in Karate

Although this work has been conducted focusing on just one technique and particular phase, some general guidelines can be drown:

- Technique phase under analysis determines the devices properties
- It is possible to combine devices with different operating features, where data acquisition in developmental phase requires lower, but in the impact phase higher OR's
- Restricted number of sensors is advisable for the reasons of avoiding athlete performance interruption and maintaining affordability
- Number and positioning of the sensors is depended on the research goal, biomechanical and common knowledge
- Positioning and attaching of the devices has to secure data acquisition free from interruption and save device from changing position
- The use of additional fasting kit ensures security positioning and increases sensor output generation.

More specific guidelines derive from the fact that most dominant pointing techniques in karate combat have similar biomechanical principles. In addition to this, punches are ballistic motions whose quantities in the moment of impact reach the highest values. Having that in mind, understanding punching biomechanics as a whole (implying all the phases from the beginning to the end of punch execution) requires devices with higher OR properties. Application of wearable devices is particularly useful in the technique analysis of the elite athletes. As already addressed it allows in-depth study and gathering data for individual approach in training design which is of outmost importance on the highest level of preparation for competition.

Since the focus is to point out the richness of diverse kinematic data acquired by sensors and possible application of wearable devices in specific combat measurement, this section presents the most illustrative cases that emphasise the informative potential of such data in technique evaluation without deeper examination of the results. Obtained signals came from hand and body sensors and represent personal kinematic signatures of each participant's RP.

8.4.1 The Hand Kinematics

Since the aim hire is to point out the richness of diverse kinematic data acquired by sensors and possible application of wearable devices in specific combat measurement, this section presents the most illustrative cases that emphasise the informative potential of such data in technique evaluation without deeper examination of the results. Obtained signals came from hand and body sensors and represent personal kinematic signatures of each participant's RP performed in RPSM modality.

The characteristics of the sample are presented in Table 8.4.1. Table 8.4.2 presents descriptive statistics: the mean ± SD of kinematics events obtained on the hand sensor. Table 8.4.3 displays the descriptive statistics for the mean ± SD of the temporal equivalents of kinematic events measured using a hand sensor, as well as the total time of the punch till impact.

Table 8.4.1. Anthropometric and experience data for each participant

Participant	Age (years)	BH (m)	BW (kg)	Experience (years)
KA_1	22	1.82	76	11
KA_2	22	1.88	86	11
KA_3	20	1.85	82	12
KA_4	24	1.85	82	11
KA_5	18	1.82	75	11
KA_6	21	1.89	75	12
KA_7	20	1.91	92	8
Mean±SD	21.00 ± 1.91	1.86 ± 0.03	81.14 ± 6.39	10.86 ± 1.35

Table 8.4.2. Descriptive statistics representing MEAN±SD of kinematics events obtained on hand sensor

Participant	HA (g0)	HAb (g0)	HV (m/s)	HRw	HRa
KA_1	-5.85 ± 0.65	9.17 ± 1.38	5.83 ± 0.40	886.85 ± 77.52	118.82 ± 7.54
KA_2	-5.68 ± 0.60	6.69 ± 0.36	6.54 ± 0.58	1,104.95 ± 396.59	82.38 ± 20.56
KA_3	-8.33 ± 0.17	8.83 ± 0.30	7.06 ± 0.67	1,225.93 ± 306.96	89.16 ± 5.45
KA_4	-6.09 ± 0.64	6.93 ± 0.50	6.91 ± 0.62	1,203.55 ± 228.95	92.11 ± 25.81
KA_5	-5.68 ± 0.67	6.78 ± 0.48	6.13 ± 0.27	1,122.02 ± 139.44	64.86 ± 12.94
KA_6	-6.90 ± 0.57	9.35 ± 0.32	6.76 ± 0.41	1,958.67 ± 244.75	105.27 ± 16.86
KA_7	-6.80 ± 0.62	8.75 ± 0.87	6.79 ± 0.60	1,309.45 ± 285.59	127.11 ± 12.33
MEAN±SD	-6.48 ± 1.05	8.07 ± 1.31	6.58 ± 0.64	1,258.77 ± 395.64	97.10 ± 24.99

Abbreviations: KA – Karate Athlete; H – hand; A – acceleration in the dominant axis of motion; Ab – absolute values of acceleration; V – velocity; Ra – rotation angle; Rw - maximum angular velocity of forearm rotation.

Table 8.4.3. Descriptive statistics representing MEAN±SD temporal equivalents of kinematics events obtained on hand sensor and total time of the punch until the impact

Participant	tHAS (ms)	tHA (ms)	tHRw	tHAb (ms)	tHV (ms)	TPt
KA_1	–299.17 ± 32.77	–147.50 ± 7.58	–14.17 ± 14.29	–150.83 ± 8.01	–41.67 ± 6.06	–360.00 ± 19.49
KA_2	–214.17 ± 11.14	–95.00 ± 39.50	–5.00 ± 0.00	–145.00 ± 30.82	–45.00 ± 6.32	–423.33 ± 186.67
KA_3	–240.00 ± 18.97	–61.67 ± 6.83	–37.50 ± 45.03	–60.83 ± 5.85	–16.67 ± 6.06	–257.50 ± 25.64
KA_4	–275.00 ± 37.15	–73.33 ± 8.16	–62.50 ± 36.16	–82.50 ± 41.20	–36.67 ± 10.80	–430.00 ± 30.17
KA_5	–215.00 ± 21.45	–70.00 ± 10.00	–86.67 ± 9.83	–98.33 ± 17.22	–33.33 ± 8.16	–255.83 ± 21.54
KA_6	–236.67 ± 35.59	–73.33 ± 9.83	–32.50 ± 13.69	–67.50 ± 11.29	–30.00 ± 10.49	–348.33 ± 125.72
KA_7	–216.67 ± 14.38	–61.67 ± 8.16	–73.33 ± 53.35	–131.67 ± 10.80	–24.17 ± 8.61	–325.83 ± 91.51
MEAN±SD	–242.38 ± 39.37	–83.21 ± 32.53	–44.52 ± 40.42	–105.24 ± 40.23	–32.50 ± 12.01	–342.98 ± 108.70

Abbreviations: KA – Karate Athlete; t – time of an event; H – hand; A – acceleration in the dominant axis of motion; Ab – absolute values of acceleration; V – velocity; Ra – rotation angle; Rw – maximum angular velocity of forearm rotation; TPt – the overall duration of the punch until the impact.

The dynamism of karate combat is reflected in quick actions.[106] Thus it is critical to understand the structure of the fast punch. Comparing the signals of hand velocity achieved by KA_2, KA_3, and KA_5 in our study, it is clear that the maximum value occurs when the hand acceleration (following the dominant axis of execution) changes polarity. KA_3 achieved the highest average hand velocity of 7.06 ± 0.67 m/s of all participants, while the average results for KA_2 and KA_5 were 6.54 ± 0.58 m/s and 6.13 ± 0.27 m/s, respectively (Figure 8.4.1.1-a). It is worth noting that TPt for the punch execution differs between KA_2, KA_3, and KA_5: –423.33 ± 186.67 ms, –257.50 ± 25.64 ms, and –255.83 ± 21.54 ms, respectively. Also, the tHV of the fastest punch is recorded at the closest time to the impact –16.67 ± 6.06 ms, in contrast to the slowest –45.00 ± 6.32 ms achieved by KA_3 and KA_2, respectively. These time parameters raise another perspective and the necessity of observing the movement in a more comprehensive manner. It is determined that RP's velocity depends on an appropriate time structure.[36]

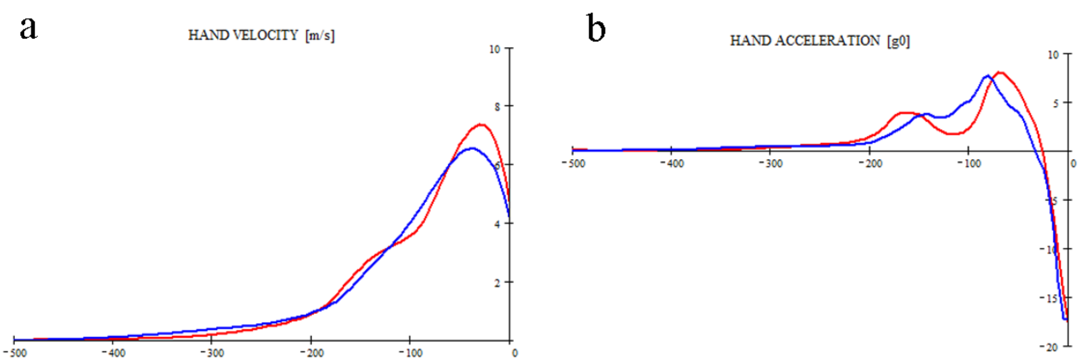


Figure 8.4.1. Hand quantities: a) hand velocity of KA_3 (red line) and KA_5 (blue line) and b) hand acceleration on the dominant axes of punch KA_3 (red line) and KA_5 (blue line)

For the above reasons, acceleration should also be taken into account. Data acquisition in this research aimed to measure hand acceleration on the dominant axis (HA) (Figure 8.4.1b) and absolute hand acceleration HAb (Figure 8.4.1a). HA is important for the obvious reasons. But valuable information also comes from HAb. For example, the group mean for HA in the present study was 6.48 ± 1.05 g_0, and for HAb, it was 8.07 ± 1.31 g_0. The fastest KA_3 achieved average HA above the group 8.33 ± 0.17 g_0 value and HAb = 8.83 ± 0.30 g_0 in the near-group range. KA_6 results show a near-group mean for HA = 6.90 ± 0.57 g_0, but the same tendency as KA_3 in HAb = 9.35 ± 0.32 g_0. A closer look at the related time parameters reveals details potentially interesting for training planning. The difference between HA and HAb in KA_3 speaks in favour of the highest HV, meaning that a particular athlete makes the fewest deviations on the path of the punch execution. In that matter, these parameters may be used as reliable technique quality indicators. Even so, they may not be enough. Additional and important data is minimal time deviation for the achieved values. On the contrary, there is discrepancy in results of KA_6 between HA and HAb implying that the athlete performs redundant movements on the lateral and vertical axis of the punch execution. Even though the final result is velocity near its highest, it questions the worth of such knowledge.

Understanding combat tactics answers the dilemma. Whether applying offensive or defensive tactics, there is constant pressure to make a score before the opponent. The point-worth punch is characterised by a great amount of energy production in the shortest time and a high level of control with regard to the opponent.[25] Since the transfer of energy and power depends on the velocity of the execution, athletes constantly aim to maximise their speed[13] but also hide the moment of the attack. Any movement that may reveal it is considered material for long-term correction training. A typical example is movement redundancy on the lateral and vertical axes, commonly adopted in the period of novice training and in the developmental phase of RP execution.

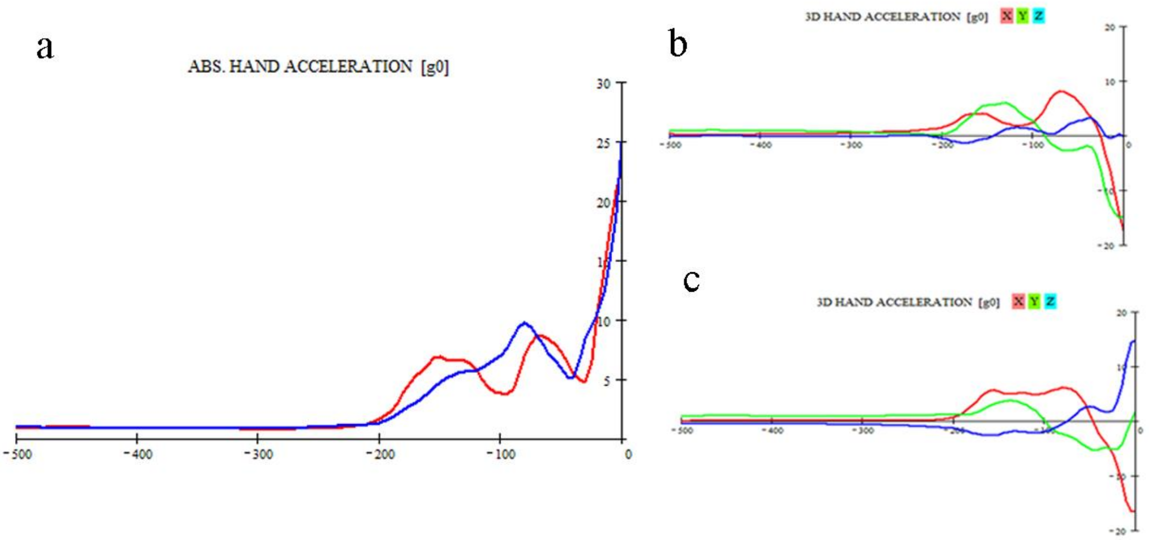


Figure 8.4.2. Hand quantities: a) abssolute hand acceleration comparing KA_3 (red line) and KA_6 (blue line), b) hand acceleration of KA_2 along *x*, *y*, and *z* axis and c) hand acceleration of KA_3 along *x*, *y*, and *z* axis (each colour representing one axis)

Aiming to comprehend the problem thoroughly, answers should be sought in the analysis of the hand movement along each axis individually (Figure 8.4.2b-c). HA and HAb, along with the accompanied temporal parameters for KA_3, have different structures compared to KA_2. While the personal signature of KA_3 speaks in favour of a proper movement pattern, this is not the case with the KA_2. On average, this athlete's time difference between the peak HA and HAb is around 50 ms (in contrast to ~1 ms for KA_3), and the execution pattern is characterised by aberrations at the start of the movement with the intention to accelerate on the horizontal plane in the second phase. It is expected that such motions will be more pronounced in less experienced and skilled competitors.[7] It is, therefore, reasonable to expect the kinematic and temporal signature of such an athlete to be characterised by a larger amount of deviation from the dominant axis and greater variation in performance.

The usual interest in the rotation of the hand during the impact was focused on the production of energy. In that regard, the significance of angular quantities is considered negligible.[136] Previous reflections on acceleration, though, provide a basis for the significance of angular kinematics to be viewed from a different perspective. As a matter of fact, the last phase in the punch execution is characterised by a sharp rotational movement and abruptly stopping the fist in contact with the target. Timely rotation of the hand brings the striking surface of the fist to the appropriate position where the back of the fist and forearm are in the same plane. This, when in contact with the impact surface, ensures the transmission of large reaction forces through the long bones of the arm.[137] From this viewpoint, angular kinematics and its timeline should have a distinct place in the analysis since a time-inconsistent rotation in the overall punch's timeline could affect performance or be a cause of injury. Also, the soon-to-start rotation of the fist in the developmental phase of the punch changes the path of the execution and affects the final outcome. It is clear that HRa and HRV (Figure 8.4.3a-b) differ between the participants in our study, but the significance of the difference would be valuable to research, as would be a correlation with other quantities and its potential effect on an impact, especially taking into account the occurrence in the overall timeline.

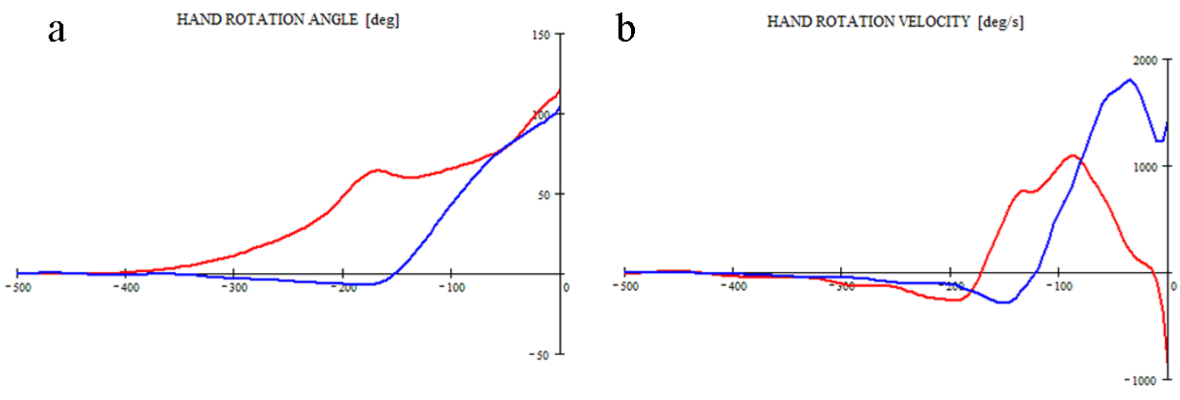


Figure 8.4.3. Hand quantities: a) hand rotation angle for KA_1 (red line) and KA_7 (blue line), b) hand rotation velocity for KA_5 (red line) and KA_6 (blue line)

8.4.2 The Body Kinematics

Tables 8.4.4 and 8.4.5 present descriptive statistics: the mean ± SD of kinematics and temporal parameters obtained on the body sensor.

Table 8.4.4. Descriptive statistics representing MEAN±SD of kinematics events obtained on body sensor

Participant	BA (g_0)	BAb (g_0)	BV (m/s)	BRa (deg)	BRw
KA_1	0.37 ± 0.28	2.13 ± 0.55	0.97 ± 0.07	–66.70 ± 6.63	–398.82 ± 19.19
KA_2	0.04 ± 0.02	1.74 ± 0.66	1.12 ± 0.14	–40.30 ± 7.64	–349.87 ± 28.78
KA_3	0.54 ± 0.22	1.90 ± 0.26	1.21 ± 0.28	–65.62 ± 8.61	–548.74 ± 30.87
KA_4	0.28 ± 0.09	1.61 ± 0.14	1.28 ± 0.15	–69.51 ± 10.08	–405.15 ± 36.69
KA_5	0.35 ± 0.05	1.55 ± 0.19	1.19 ± 0.17	–74.02 ± 2.14	–458.56 ± 17.74
KA_6	0.22 ± 0.16	2.35 ± 0.50	1.34 ± 0.23	–80.20 ± 1.78	–524.19 ± 22.77
KA_7	0.35 ± 0.12	2.42 ± 0.50	1.18 ± 0.12	–57.00 ± 9.71	–400.59 ± 15.78
MEAN±SD	0.31 ± 0.21	1.96 ± 0.53	1.18 ± 0.20	–64.76 ± 13.93	–440.85 ± 72.23

Abbreviations: KA – Karate Athlete; B – body; A – acceleration in the dominant axis of motion; Ab – absolute values of acceleration; V – velocity; Ra – rotation angle; Rw – maximum angular velocity of pelvis rotation.

Table 8.4.5. Descriptive statistics representing MEAN±SD temporal equivalents of kinematics events obtained on body sensor

Participant	tBAS (ms)	tBA (ms)	tBAb (ms)	tBV (ms)	tBRS	tBRa (ms)	tBRw (ms)
KA_1	–271.67 ± 34.74	–285.00 ± 53.10	–168.33 ± 72.78	–107.50 ± 13.32	–235.83 ± 16.86	105.00 ± 20.49	–122.50 ± 18.91
KA_2	–194.17 ± 16.86	–423.33 ± 186.67	–166.67 ± 10.80	–61.67 ± 7.53	–200.83 ± 27.46	–21.67 ± 6.83	–93.33 ± 35.87
KA_3	–188.33 ± 16.33	–171.67 ± 14.72	–141.67 ± 13.66	–58.33 ± 4.08	–217.50 ± 32.83	–15.83 ± 8.01	–70.00 ± 11.83
KA_4	–305.00 ± 54.77	–223.33 ± 103.47	–97.50 ± 32.37	–56.67 ± 41.07	–267.50 ± 6.89	53.33 ± 67.87	–115.83 ± 35.84
KA_5	–239.17 ± 21.08	–210.00 ± 20.74	–132.50 ± 29.96	–25.00 ± 21.91	–255.83 ± 21.54	10.83 ± 29.57	–102.50 ± 21.62
KA_6	–169.17 ± 21.54	–247.50 ± 173.92	–141.67 ± 7.53	4.17 ± 18.28	–202.50 ± 16.36	46.67 ± 10.33	–61.67 ± 11.25
KA_7	–230.00 ± 22.58	–218.33 ± 16.02	–156.67 ± 44.01	–80.00 ± 8.37	–229.17 ± 11.58	26.67 ± 31.57	–91.67 ± 14.72
MEAN±SD	–228.21 ± 53.13	–254.17 ± 125.06	–143.57 ± 41.06	–55.00 ± 38.62	–229.88 ± 30.59	29.29 ± 50.64	–93.93 ± 30.17

Abbreviations: KA – Karate Athlete; t – time of an event; B – body; A – acceleration in the dominant axis of motion; Ab – absolute values of acceleration; V – velocity; S – start of pelvis rotation; Ra – rotation angle; Rw – maximum angular velocity of pelvis rotation.

Unlike the hand acceleration, where the sample difference is about 1.2 times between HAb and HA, the discrepancy between BAb and BA was evidently greater, as much as 5.3 times on average. While it is very important for the movement of the hand that the dominant path is in the horizontal plane, the path of the body motion is somewhat different. When it comes to the body, the necessary stance stability as a ground for effective execution is achieved by moving the body in all three axes. Also, the time of occurrence of these parameters shows that the tested athletes have a different timeline structure. KA_3 acceleration onset is recorded as –188.33 ± 16.33 ms before impact and BA on the horizontal plane as of 0.54 ± 0.22 g_0 (Figure 8.4.4-a). In contrast, KA_5 and KA_7 accelerate from close by –230 ms to the impact and achieve similar BA of ~0.35 g_0.

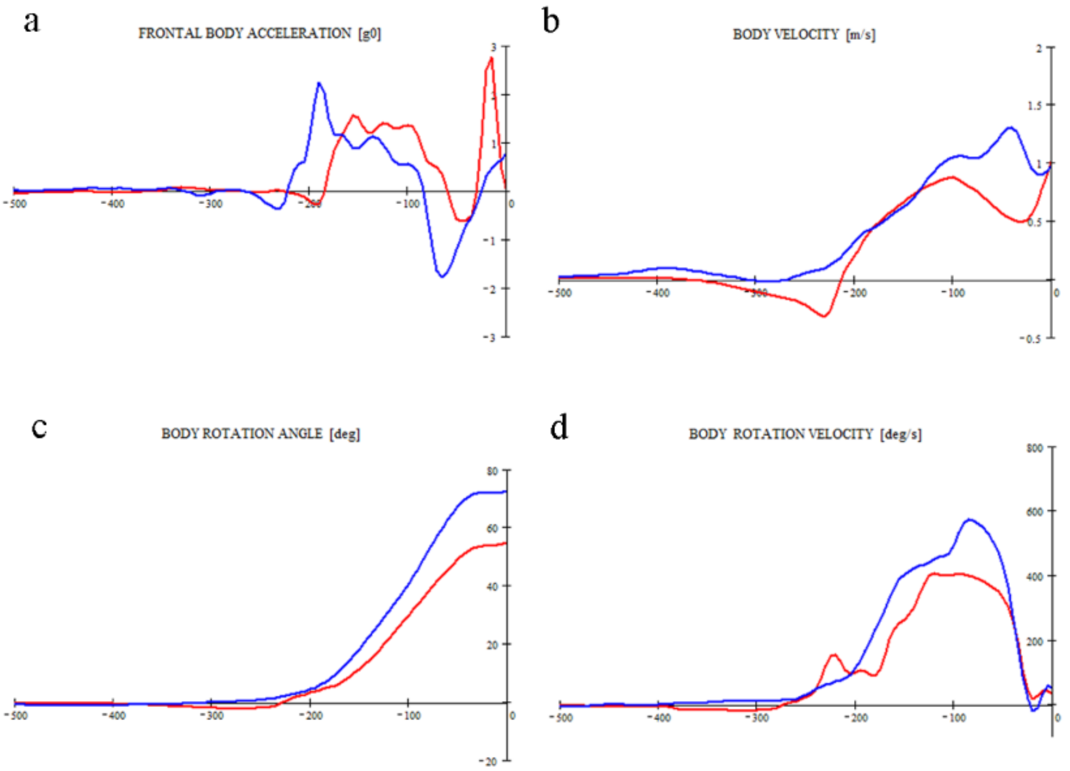


Figure 8.4.4. Body kinematics: a) frontal body acceleration for KA_3 (red line) and KA_7 (blue line), b) body velocity for KA_1 (red line) and KA_4 (blue line), c) body rotation angle for KA_1 (red line) and KA_3 (blue line), and d) body rotation velocity for KA_1 (red line) and KA_3 (blue line)

The absolute body acceleration values for P_3, P_5, and P_7 were as follows: 1.90 ± 0.26 g_0, 1.55 ± 0.19 g_0, and 2.42 ± 0.50 g_0, respectively, and BAb can be regarded as a reliable indicator of body movement. But a comprehensive understanding of these parameters and conceivable differences in athletes' performance is possible only with regard to BV and HV, as well as their components. Studying the effect of BV on HA and HV would be intriguing. Comparing KA_1 and KA_4, it is noticeable that achieved values differ, and this is revealed in the personal signature of an athlete recorded by the body sensor (Figure 8.4.4b). For example, KA_1 reaches an average low punch velocity of 5.83 ± 0.40 m/s, supported by a BV of 0.97 ± 0.07 m/s. In contrast, KA_4 achieves HV 6.09 ± 0.64 m/s on average and a higher BV of 1.28 ± 0.15 m/s.

Kinematic studies of RP so far suggest that a deeper insight into the relationship between the angular quantities of the body and key hand parameters might clarify punch execution outcomes. For better understanding, lumbopelvic control is arguably an important contributor to the kinetic energy and force output[132] affecting punch velocity.[7] Suppose that it is not just enough to reach the expected angle to ensure efficient transmission of energy. As it is suggested, the right timing,[36] along with the sharp interruption of the pelvis angular motion, could be the answer. The values of angular kinematics in our study (Figures 8.4.4c-d) show differences in personal performance signatures. Just note that the body rotation angle is measured about the vertical axis from the beginning of the movement, and it reaches its maximum value slightly after the impact. KA_1 and KA_3 start the BRa in a close time window of –235.83 ± 16.86 ms and –217.50 ± 32.83 ms and achieve a high BRa of 66.70 ± 6.63 deg and 65.62 ± 8.61 deg for KA_1 and KA_3, respectively. But the interesting part is that for KA_1, that happens after the impact, and in the case of KA_3 it is evidenced 15 ms before impact. The angular velocity data for these participants also differs: 398.82 ± 19.19 deg/s and 548.74 ± 30.87 rad/s for KA_1 and KA_3, respectively. The same is true for the accompanied timeline. Theoretical knowledge as well as the presented findings indicate the potential effect of BRa and BRV on BV and HV and associated parameters.

9. General Conclusion

The primary objective of this study was to investigate the RP execution of individuals with exceptional qualities. In order for the internal validity of the study to be higher, the methodological approach was focused on the collection of multiple sources of evidence. Taking that into account, the suggested model of investigation, employing specific tests and easy-to-use equipment, can be regarded as suitable, especially in the case analysis of elite athletes.

The main aim of this work was to determine if the different modalities of punch execution, consisting of different levels of kinetic chain involvement, affect punch efficiency. Velocity of RP and acceleration of the body and hand were selected as parameters of efficiency. In addition to that, temporal parameter data were analysed. The results of the three stages of research were published in three separate studies. The initial necessary step was finding an appropriate methodological solution for investigation in real surroundings and, in accordance with that, choosing a proper measurement device. Therefore, the first study aimed to investigate the issue of data collection within the context of realistic sports environments by applying custom-made wearable kinematic measurement tools. The metrical qualities and accuracy of the KS were submitted for evaluation. The second study addressed the methodology problem and presented a novel approach to the investigation of elite karate fighters through ten specific tests utilising KS. The third study focused on the variability and correlation of chosen kinematic and accompanied time parameters of RP performed in chosen test modalities.

In relation to research hypotheses, the following can be concluded:

HG: The hypothesis in relation to IMU sensors' technology reliability and discriminatory potential with respect to the specific indicators of the reverse punch within different modalities of performance (Study #1) is that the measurement device will provide a valid base of data; it can be concluded that the hypothesis has been accepted.

Regarding the qualitative criterion of ICC significance, it was noted that eight kinematic variables exhibited good reliability, with an ICC range of 0.75-0.90. Additionally, 10 kinematic variables showed excellent reliability, with an ICC value exceeding 0.90. The moment of occurrence has the lowest reliability values, whilst the peak of acceleration demonstrates the highest levels of reliability. KS can be regarded as an advanced measuring instrument that offers a dependable foundation of information for the purpose of objectifying assessment, particularly in relation to elite athletes.

H1: The hypothesis in relation to the kinematic parameters in the developmental phase of the reverse punch between the tests (Study #2) is that there is difference a between observed parameters in regard to the modalities; it can be concluded that the hypothesis has been accepted.

The results revealed that the exclusion or inclusion of the body segments affects kinematic parameters. The sliding action preceding rapid punches yielded the highest acceleration values, both in static (7.35 ± 0.47 g_0) and dynamic (6.99 ± 1.23 g_0) tests, while a partner held a chest punch pad. The aforementioned principles also hold true for the measurements of velocity, which are recorded as 8.39 ± 0.14 m/s and 7.30 ± 1.28 m/s, respectively.

H2: The hypothesis in relation to the appearance time of the kinematic events (Study #2) is that they are structured in a recognisable pattern; it can be concluded that the hypothesis has been accepted.

While the specific timing of the kinematic event varied among modalities, it is apparent that the timeline structure remained reasonably consistent, with the highest hand velocity consistently recorded as the final event in the observed temporal sequence. The achievement of a suitable time pattern of kinematic events is observed under situations that exhibit lower variability, specifically in the context of a static test. This timeline denotes the temporal proximity to the impact event, whether it corresponds to tHA, tBV, or tHV.

H3: The hypothesis about the kinematic and temporal parameters of the body and hand during the developmental phase of punch (Study 3) is that there is a correlation between parameters; the hypothesis has been accepted.

A significant association was seen between the tHV:tHA, BA:tBA, tBV:tBA, and BRa:BV, accounting for 57%, 36%, 34%, and 30% of the variation, respectively. The correlation coefficients for 17 pairs of variables were calculated and found to be of medium strength.

It can be concluded that the capture of in situ data in realistic performance settings allows for a practical application that facilitates the comprehension of the genuine magnitude of the relationship between the segments of the kinetic chain and the kinematic disparities observed in the examined approach. The multiple-case analysis showed that, except for some general similarities, personal signatures in execution can be recognised in specific kinematic and temporal patterns affecting the final outcome. Such evidence is the groundwork of appropriate instruction in technique improvement at the highest sports level and justifies the individual approach in the performance analysis and training design.

Proposed strategy redirects the training emphasis of high-level athletes towards the specific nuances that are common among combat sports. This phenomenon gives rise to the analysis of enhancement techniques that extend beyond the boundaries of karate as a discipline. In addition, the utilisation of targeted assessments in conjunction with strategically placed measurement instruments yields significant data, facilitating impartial evaluation that serves as a foundation for enhancing both training and competitive performance.

In short, the contribution of the study is in the field of:

- Improving the training and competitive practice of elite-level karate athletes through indication of the potentially weak points in the RP execution
- Understanding the kinematic and temporal punch patterns in the developmental phase of RP in different modalities of execution as a foundation for individual approaches to enhancing punch efficiency
- Improvement of the testing procedures and study methodology with the employment of sensors and specific tests in the most researched karate technique
- Enhancing punch control and performance through the application of novel approaches leads to a higher level of efficiency due to the reduction of poor movement structure.

10. References

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11. Appendices

11.1 Ethics Committee Approval

CERTIFIED TRANSLATION FROM SERBIAN INTO ENGLISH

Stamp: Republic of Serbia, University of Belgrade
Faculty of Sport and Physical Education
02 no. 484-2
24 February 2011
Belgrade, Blagoja Parovica 156

UNIVERSITY OF BELGRADE
FACULTY OF SPORT AND PHYSICAL EDUCATION

APPROVAL OF THE ETHICS COMMITTEE OF THE FACULTY OF SPORT AND PHYSICAL EDUCATION, UNIVERSITY OF BELGRADE FOR EXECUTION OF THE PROJECT "EFFECTS OF THE APPLIED PHYSICAL ACTIVITY ON LOCOMOTOR, METABOLIC, PSYCHO-SOCIAL AND EDUCATIONAL STATUS OF THE POPULATION OF THE REPUBLIC OF SERBIA" (No. 47015)

Based on the inspection of the plan of the project "Effects of the Applied Physical Activity to Locomotor, Metabolic, Psycho-Social and Educational Status of the Population of the Republic of Serbia" (No. 47015, project leader assistant prof. Milivoj Dopsaj, PhD), approved by the Ministry of Science and technological development of the Republic of Serbia within the cycle of national scientific projects for the period from 2011 to 2019, the Ethics Committee of the Faculty of Sport and Physical Education of the University of Belgrade considers that both in research conception and execution planning as well as in the application of the obtained results, from its beginning the project has been undertaken based on the principles which comply with ethical standards, ensuring thus protection for human subjects from possible violation of their psycho-social and physical benefit.

In conformity with the aforesaid opinion, the Ethics Committee of the Faculty of Sport and Physical Education of the University of Belgrade has granted the approval for realization of the research planned by the project "Effects of the Applied Physical Activity to Locomotor, Metabolic, Psycho-Social and Educational Status of the Population of the Republic of Serbia" (No. 47015, project leader Assistant prof. Milivoj Dopsaj, PhD) which is approved by the Ministry of Science and technological development of the Republic of Serbia within the cycle of national scientific projects for the period from 2011 to 2019.

For the Ethics Committee
full prof. Dušan Ugarković, signed
associate prof. Vladimir Koprivica, signed
(Stamp)

END OF TRANSLATION

№ 178/11

I CERTIFY THAT this document which has been given to me in Serbian language, has been correctly translated into English.

IN WITNESS WHEREOF I have hereunto set my hand and seal, this 1st day of March 2011 in Beograd.

My appointment is permanent.

GORDANA VEKARIĆ

Gordana Vekarić, Sworn to Court
Interpreter for English and Italian language
Milutina Milankovića 130/33, Beograd, Serbia
tel:++381 11 711 03 38
e-mail:gocaa@eunet.rs

Appointed by the Decision of the Republic Minister of Justice.
Belgrade, Serbia № 74-02-46/91-03

11.2 Published Paper I

Measurement 177 (2021) 109315

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Measurement

journal homepage: www.elsevier.com/locate/measurement

Metrical characteristics and the reliability of kinematic sensor devices applied in different modalities of reverse punch in karate athletes

Vesna Vuković [a,*], Milivoj Dopsaj [a,b], Nenad Koropanovski [c], Stefan Marković [a], Anton Kos [d], Anton Umek [d]

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[c] University of Criminal Investigation and Police Studies, Belgrade, Serbia
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ARTICLE INFO

Keywords:
Wearable sensors
Acceleration
Motion pattern
Karate
Gyako tsuki

ABSTRACT

In order to understand the complexity of punches, measurement under realistic conditions in a training environment is necessary. A crucial element to achieving valid results is a reliable instrument. The aim of the study was to evaluate the metrical characteristics and reliability of kinematic sensors (KS) in specific karate testing as a novel method in the training process. Fourteen male competitors, members of a Serbian national senior and cadet karate team, participated in the study. Segmental acceleration in the different modalities of reverse punch *(Gyako tsuki)* were measured using KS placed on the hand and body. In relation to the qualitative criterion of the intraclass correlation coefficient (ICC) significance, good reliability (ICC = 0.75–0.90) was observed for eight kinematic variables, while excellent reliability (ICC > 0.90) was confirmed for ten kinematic variables. KS can be considered sophisticated measuring tools providing a reliable base of information for the objectification of assessment as the primary approach to top-level athletes.

1. Introduction

Punches are the most recognizable arm technique in various combat sports [1], karate being one of them. While there are some similarities with other combat sports, the basic idea of karate as a martial art makes it specific. In short, its essence is inflicting lethal damage to an opponent with one strike. The same principle – albeit with an alteration that involves control over the opponent – is demonstrated in sports combat. A scoring advantage is the outcome of a highly efficient technique that is supported by stance stability [2]. It is accomplished by taking longer stances with a lower centre of gravity, as well as explosive and ballistic technique execution. Furthermore, it means it is necessary to use all biological capacities in order to achieve maximal efficient technique. This in turn implies a rapid movement in space with the introduction of as much body mass as possible in the final segment delivering the impact. In order to understand such complexity, kinematical analysis would provide useful feedback. This issue has mainly been explored under laboratory conditions, using either a force platform or electromyography in combination with reflective markers and cameras [2–6]. Due to the complexity of the human neuromuscular and skeletal systems [7], this approach requires the usage of expensive and extensive equipment, as well as experts who will use it correctly, thus reducing the scope of applications. Some authors, however, emphasize the importance of measurement under realistic conditions in a training environment [8,9]. This might be achievable through the application of wearable sensors, which are rapidly becoming integrated in the broad field of human movement and sport research, providing monitoring out of laboratory settings [10–12]. Even so, it appears that new technology in combat sports has not been subjected to extensive application [13].

In combat sports studies (including boxing, judo, taekwondo and karate), inertial sensors are used in more than one domain: improvement of the competition [14] and training process [15], technical modelling [16], as well as equipment [17], performance and technique analysis [8,9,18–22]. Different approaches have been applied, such as placing sensors on the equipment used in the sport, on the athlete, or on both. Regardless of the positioning, angular velocities, force or translational and rotational accelerations that are identified as key parameters in combat sports [9,19,1] were acquired. For karate technique,

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11.3 Published Paper II

applied sciences

MDPI

Case Report

Specific Test Design for the In-Depth Technique Analysis of Elite Karate Competitors with the Application of Kinematic Sensors

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Abstract: Karate fighters are under constant pressure to find adequate scoring solutions in ever-changing combat conditions. Thus, technique improvement at high levels of mastery demands a novel approach to key data acquisition and in-depth analysis of more than just the impact phase in punch execution. With the aim of describing the kinematic and temporal structure of a reverse punch in the developmental phase, two wireless sensors were used for the acquisition of selected quantities in ten modalities performed by a continental and world medallist. The results show that the timeline of kinematic parameters may be a reliable factor regarding the efficiency of the reverse punch. The obtained hand results show a tendency towards maintaining greater levels of stability in comparison to the body. Additionally, the differences between parameters in relation to applied tests that replicated training and combat conditions were noted. The highest acceleration values were obtained in sliding motion preceding RP, with a partner holding chest punch pad, both static (7.35 ± 0.47 g_0) and dynamic (6.99 ± 1.23 g_0) tests. The same applies for velocity (8.39 ± 0.14 and 7.30 ± 1.28 m/s). The obtained results indicate the need for specific testing and an individual approach in the analysis of the techniques of elite competitors, along with the use of sensors in data acquisition. Such an approach may help improve the training and competition practice of karate fighters.

Keywords: reverse punch; standardised testing; elite athletes; wireless technology

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Citation: Vuković, V.; Koropanovski, N.; Marković, S.; Kos, A.; Dopsaj, M.; Umek, A. Specific Test Design for the In-Depth Technique Analysis of Elite Karate Competitors with the Application of Kinematic Sensors. *Appl. Sci.* **2022**, *12*, 8048. https://doi.org/10.3390/app12168048

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1. Introduction

In constant pursuit of surpassing achieved results, elite athletes uphold high training standards. Such standards can be met by overcoming conventional training methods [1] based on the subjective evaluation of an individual athlete's coaches, and focused technique analysis may help the process. Stemming from the diversity of a methodological approach, in the broadest sense [2,3], the limiting factors in technique analysis of combat sports are numerous. Analysis of the reverse punch (RP), the most prominent karate technique, is no exception.

The distinguishing characteristic of karate combat at an elite level is the preference for variability in fighting conditions [4]. Despite the fact that direct attack accounts for the majority of points [5], it is not the only scoring modality [5–7]. Consequently, fighters are under constant pressure to find and apply adequate solutions [4,8]. Scoring efficiency depends on a fighter's ability to adapt accordingly [8] in restricted periods of fighting activity under high intensity [6,7,9]. Thus, it would be beneficial to research and analyse RP in realistic combat and training environments, addressing the issues which, due to their complexity, were considered separately in previous research [10–16].

11.4 Published Paper III

applied sciences

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Article

Variability and the Correlation of Kinematic and Temporal Parameters in Different Modalities of the Reverse Punch Measured by Sensors

Vesna Vuković [1,*], Anton Umek [2], Milivoj Dopsaj [1], Anton Kos [2], Stefan Marković [1] and Nenad Koropanovski [3]

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3 Department of Criminalistics, University of Criminal Investigation and Police Studies, 11800 Belgrade, Serbia; nenad.koropanovski@kpu.edu.rs
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Abstract: The influence of joint motion on punch efficiency before impact is still understudied. The same applies to the relationship between the kinematic and temporal parameters of a reverse punch (RP) that determines a score. Therefore, the aim of this study was to investigate if the exclusion or inclusion of body segments affects the acceleration, velocity, rotation angle, and timeline of execution, and to examine the correlation between these quantities. Seven elite male competitors—senior European and World Championship medalists—participated in the in-field testing. Quantities were acquired in the developmental phase of RP through three modalities of execution. Synchronized real-time data were obtained using combined multimodal sensors and camera fusion. The main findings of the study have highlighted the significant differences in the temporal and kinematic variables of RP that arise from the modality of execution. Large and medium correlation coefficients were obtained between the examined variables of body and hand. In conclusion, the results show that measured parameters are affected by segmental body activation. Moreover, their interdependence influences punch execution. The presented interdisciplinary approach provides insightful feedback for: (i) development of reliable and easy-to-use technical solutions in combat sports monitoring; and (ii) improvements in karate training.

Keywords: karate; technique analysis; acceleration; velocity; rotation angle; timeline; wearable devices

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Citation: Vuković, V.; Umek, A.; Dopsaj, M.; Kos, A.; Marković, S.; Koropanovski, N. Variability and the Correlation of Kinematic and Temporal Parameters in Different Modalities of the Reverse Punch Measured by Sensors. *Appl. Sci.* **2023**, *13*, 10348. https://doi.org/10.3390/app131810348

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1. Introduction

The difference between a punch that is point-worthy and one that is not can be a few milliseconds. Besides the permanent adjustment imposed by the karate combat environment [1] and a number of adaptive interactions between the nervous and musculoskeletal systems [2], the relationship between the kinematic and temporal parameters of the motion may be one of the main determinants of a successful outcome. Strictly speaking, attention should be directed to acceleration, velocity, rotation angle, and temporal parameters. The temporal parameters are defined as the equivalent of the kinematic event occurring during the corresponding characteristic phase of the punch execution in the optimal time sequence. Joint kinematics are traditionally restricted to laboratory research [3,4]. Available detection systems are typically robust, expensive, and demand trained experts who know how to operate them [5,6]. In such settings, athletes face limitations that are not common in competition and training [6]. Consequently, constraints imposed by the equipment and environment may affect the motor skill under analysis [3]. In contrast, the acquisition of a wide range of diverse data in situ using kinematic sensors (KS) enables measuring during

11.5 Biography

Vesna Vuković

was born on April 25, 1977 in Belgrade.

In 1995, she graduated from the III Belgrade Gymnasium.

In 2016, she graduated from academic studies at the Faculty of Physical Education and Sports Management in Belgrade.

In 2017, at the same faculty, she earned the title of Master of Physical Education and Sports and enrolled in doctoral studies at the Faculty of Sports and Physical Education in Belgrade.

She has been actively engaged in karate since 1987 as a competitor, trainer, and referee, holding European and World licences.

Since 2019, she has been employed at Elementary School "Mladost" as a subject teacher of physical and health education.

She speaks English.

11.6 Bibliography

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Marković S, Kos A, **Vuković V,** Dopsaj M, Koropanovski N, Umek, A. Use of IMU in Differential Analysis of the Reverse Punch Temporal Structure in Relation to the

Achieved Maximal Hand Velocity. *Sensors*, 2021;21(12): 4148. https://doi.org/10.3390/s21124148

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11.7 The Form 5

образац изјаве о ауторству

Изјава о ауторству

Име и презиме аутора **Весна Б. Вуковић**

Број индекса **5006/2017**

Изјављујем

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Изјава о истоветности штампане и електронске верзије докторског рада

Име и презиме аутора: **Весна Вуковић**

Број индекса: **5006/2017**

Студијски програм: **Експерименталне методе истраживања хумане локомоције**

Наслов рада: **Kinematic and temporal parameters in different modalities of the reverse punch measured by IMU sensors**

Кинематички и временски показатељи ударца гјаку зуки у различитим модалитетима извођења мерени IMU сензорима

Ментор: **проф. др Миливој Допсај**

Изјављујем да је штампана верзија мог докторског рада истоветна електронској верзији коју сам предао/ла ради похрањивања у **Дигиталном репозиторијуму Универзитета у Београду**.
Дозвољавам да се објаве моји лични подаци везани за добијање академског назива доктора наука, као што су име и презиме, година и место рођења и датум одбране рада.
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Потпис аутора

У Београду, ________________________

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11.9 The Form 7

образац изјаве о коришћењу

Изјава о коришћењу

Овлашћујем Универзитетску библиотеку „Светозар Марковић“ да у Дигитални репозиторијум Универзитета у Београду унесе моју докторску дисертацију под насловом:

KINEMATIC AND TEMPORAL PARAMETERS IN DIFFERENT MODALITIES OF THE REVERSE PUNCH MEASURED BY IMU SENSORS

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