The ground reaction forces in basic stances in shotokan karate as an effective indicator in the prevention of lower limb pain in competitive athletes

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Anna Lisowska [ABDE], **Anna Fryzowicz** [BD], **Jacek Mączyński** [BC], **Małgorzata Ogurkowska** [ADE]

Department of Biomechanics, Poznan University of Physical Education, Poznan, Poland

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Abstract

Background and Study Aim: Shotokan karate training is based on learning basic stances. Improving the stances in the training process can have a significant impact on the loading of lower limb joints. Given frequent pain symptoms in the area of the knee joints among professional shotokan karate athletes, the aim of this study was knowledge about the magnitude of lower limb dynamic load indicators while performing three basic *kata* stances.

Material and Methods: Participants (n = 15) were male shotokan karate *kata* athletes (aged 27.5 ±8 years; training experience of 17.5 ±4.8 years). During the study, the ground reaction forces (GRFs) during dynamic transitions were measured. The following functional tests were also performed: Thomas test, Ober test and Patrick test, verifying the occurrence of lower limb muscle contractures. The Foot Posture Index Test was also performed.

Results: The GRFs occurring in basic karate stances were statistically significantly different ($p<0.05$). In the *zenkutsu dachi* and *kokutsu dachi* stances their vertical components reached values more than three times higher than the athletes' body weight. All three basic stances (also *kiba dachi*) showed statistically significant ($p<0.05$) higher values of the anteroposterior component of GRFs in the group of *kata* athletes; the occurrence of lower limb muscle contractures, especially hip abductors, was also demonstrated.

Conclusions: Due to the impact of the anteroposterior component of GRFs, the *kiba dachi* is considered to be the most dangerous stance. In order to avoid chronic overload changes of the musculoskeletal system, preventive measures should be implemented for *kata* athletes. These should focus on minimizing the generated GRFs and preventing muscle contractures.

Key words: *kiba dachi* • knee joint • *kokutsu dachi* • load • *zenkutsu dachi*

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Author's address: Anna Lisowska, Department of Biomechanics, Poznan University of Physical Education, Królowej Jadwigi St. 27/39, 61-871 Poznan, Poland; e-mail: ania.lisowska90@gmail.com

Martial arts – *plural noun* any of various systems of combat and self-defence, e.g., judo or karate, developed especially in Japan and Korea and now usually practised as a sport [32].

Kata – *noun* a sequence of movements in some martial arts such as karate, used either for training or to demonstrate technique [32].

Kumite – is a semi-contact karate competitive concurrence, where two athletes perform various kicking, punching, and blocking techniques towards each other with maximum control in order to gain points and win the match. Destruction is fictive.

Technique– *noun* a way of performing an action [32].

Dan (dan'i) – a term used to denote one's technical level or grade [33].

Kyū – the series of grades that precede *dan* ranks. *Ikkyū* is the grade immediately below *shodan* [33].

Load – *noun* **1.** a weight or mass which is supported **2.** the force that a body part or structure is subjected to when it resists externally applied forces **3.** the amount of something, usually weight, that a body part can deal with at one time [32].

Training session – *noun* a period of time during which an athlete trains, either alone, with a trainer or with their team [32].

Performance – *noun* the level at which a player or athlete is carrying out their activity, either in relation to others or in relation to personal goals or standards [32].

INTRODUCTION

Shotokan (s*hōtōkan*) karate is a martial art which originated in Okinawa, Japan, and was founded by Gichin Funakoshi. Karate training consists of the practice of basic techniques (*kihon*), sparring (*kumite*) and *kata*. In Japanese, *kata* means "basic form". It is a sequence of strictly defined movements for defence and attack performed as if fighting many opponents attacking from different sides. These techniques were developed by great masters and are always performed in the same order [1-3]. A significant part of karate training consists in practising the stances, which may translate into high loading of hip and ankle joints, and in particular knee joints [4-7]. The basic shotokan karate stances that most often recur in *kata* are: *zenkutsu dachi*, *kokutsu dachi* and *kiba dachi* [8]. The positions and controlling the centre of mass of the athlete is of crucial importance in most of the martial arts [9]. Studies carried out on nine male black belts with an average of more than thirty years of training experience have shown that the weight distributions for those three stances did not present a significant difference between the population mean and the postulated values in the weight distributions, at 0.05 of probability [10]. This is indicative of the fact that the proportions of loading of lower extremities defined in the literature, depending on the position in advanced karate athletes, are in accordance with the applicable standards (Table 1).

The level of karate skills is assessed not only on the basis of *kyu* or *dan* exams, but also on the basis of participation in sports competitions [12].

The criteria for advanced performance of *kata* are defined in the regulations of the European Shotokan Karate-do Association. Referees assess the correct order of techniques, control of force, tension and relaxation, speed, and rhythm, and stopping. The direction of movement, understanding of *kata* and *embusen*, i.e., the beginning and ending the sequence in the same place, are also assessed. Points are also awarded for head movements, positions, balance, coordination, and accuracy. The harmony of movement, *kiai*, i.e., shout, and breathing are also important. Eye focus, fighting spirit and ceremony are also evaluated [13].

Sports competition at the highest level usually requires the athletes to define their specialization as *kata* or *kumite* [14], which also causes specific adaptation of the body. Elite *kata* athletes are characterized by high explosive muscle strength, balance, and flexibility, which plays a key role in this discipline [15-18]. Lower limb joints, especially knee joints, are the most frequent location of pain among *kata* athletes [11]. However, it has been verified that the cause is not the hamstrings to quadriceps disproportion, and the common occurrence of bilateral deficit in this discipline has been excluded [18]. It should be emphasised that practicing sports professionally may contribute to the occurrence of overload changes in the musculoskeletal system [6, 19].

The following premises and assumptions are at the basis of the cognitive goal of our research: a) dynamic loads determined by the ground reaction forces (GRFs) may cause internal loads and increase the risk of overload knee injuries as a result of repeating the sequences of *kata* movements many times; b) there are of frequent pain symptoms in the area of the knee joints among professional shotokan karate athletes; c) functional tests concerning contractures of the lower limb muscles allow to determine their statistical relationships with the GRFs in *kata* training; d) understanding the pathobiomechanism of overload changes in the musculoskeletal system in this group of athletes may lead to the development of prevention of lower limb joint ailments.

The aim of this study was knowledge about the magnitude of lower limb dynamic load indicators while performing three basic *kata* stances.

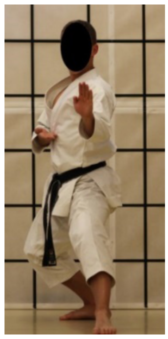
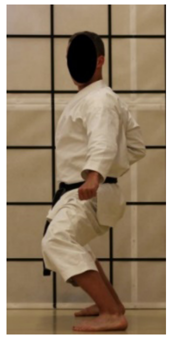
MATERIAL AND METHODS

Participants

Subjects (n = 15) participating in this study were male shotokan karate *kata* competitors (aged 27.5 ±8 years; height 178.7 ±6.3 cm; body mass 78.7 ±6.1 kg; BMI 24.7 ±2.5 kg/m2). Training experience of the whole group was on average 17.5 ±4.8 years. The average training experience ratio calculated on the basis of age was 64 ± 8.5%. The levels of advancement ranged from 3 *kyu* to 4 *dan*.

A total of 15 *kata* athletes were qualified for the main test in the biomechanical laboratory. The inclusion criteria were as follows: a minimum training experience of 12 years and no injuries sustained in the preceding 6 months. The test was preceded by a 10-minute warm-up on a stationary bicycle and individual 5-minute stretching.

Table 1. Basic karate stances [11].

View	Stance		
	zenkutsu dachi	*kokutsu dachi*	*kiba dachi*
Front			
Side			

The laboratory tests with human participants were approved by the Bioethics Committee at Poznan University of Medical Sciences (approval No. 624/15). Before the study was commenced, each athlete was acquainted with the characteristics of the tests and the associated risks, and voluntarily agreed to participate in the study.

Measurement of GRFs

Kistler type 9281C piezoelectric platform, 40 x 60cm in size, was used to measure the GRFs during performance of transitions in stances. Type of load amplifier: 9865B1Y28; measurement sampling frequency: 1000Hz; connection to a computer with a 12-bit analogue-digital converter. On the platform, data from the front leg were recorded in dynamic transitions reflecting the conditions of *kata* competitions. Transitions to the left and right side in the following stances: 1) *zenkutsu dachi age uke gyaku zuki*; 2) *kokutsu dachi shuto uke*; 3) *kiba dachi gedan barai* were measured three times. Maximum values of the three components of GRFs: vertical (F_Y), antero-posterior (F_Z) and lateral-medial (F_X) were considered for the analysis of the selected stances. The results were presented as relative force values, i.e., the quotient of the maximum GRF to the athlete's body weight [N/kg]. Then the mean values of the examined group and standard deviation were determined.

Foot Posture Index Test

The correctness of foot shape was evaluated using the Foot Posture Index Test (FPIT). During the functional test, 6 components are evaluated which are indicative of whether a foot is neutral or deviations towards pronation or supination occur: 1) talar head palpation, 2) supra & infra lateral malleolar curvature, 3) inversion/eversion of calcaneus, 4) bulging in talonavicular joint, 5) congruence of the medial longitudinal arch, 6) abduction/adduction of the forefoot on the rearfoot [20].

Functional tests

Functional tests, i.e., Thomas test, Patrick test and Ober test, were also carried out to verify the occurrence of lower limb muscle contractures. Verification of the occurrence of contractures in the tested muscles allowed to compare the relative GRFs depending on the occurrence or absence of muscle contractures. This article shows the values of these forces, which differ significantly in both groups, broken down into the right and left lower limb. For the purposes of data presentation, the muscles that take an active part in performing dynamic transitions in basic stances were selected. The analysis of the median values of the GRFs, which were obtained for selected stances by athletes with and without muscle contractures, broken down into the left/right lower limbs has been made.

Statistical analysis

All statistical analyses were conducted with the use of TIBCO Statistica® ver. 13. Normality of distribution was verified using the Shapiro-Wilk test. Then, in the absence of normal distributions, the non-parametric Spearman's rank correlation test was used for the analysis. The Mann-Whitney U test was used to demonstrate statistical significance of differences in median GRFs of lower limbs for two groups of athletes (with and without muscle contractures). Tukey's HSD test was used to show the differences between the GRFs in particular stances. In the studies, the level of at least $p<0.05$ and higher was shown as statistically significant differences.

RESULTS

The GRFs occurring in basic karate stances were statistically significantly different ($p<0.05$). The highest maximum values of GRFs of the examined *kata* athletes were obtained in the measurement of the vertical component in the *zenkutsu dachi* stance. Higher values were generated by the right lower limb in all three stances. In the *zenkutsu dachi* stance, significantly higher values of the vertical component of the right lower limb were observed in relation to the left lower limb in the *kiba dachi* stance ($p = 0.019$). Additionally, a tendency towards statistically significantly higher values of vertical GRFs in the *zenkutsu dachi* stance was observed in relation to the *kiba dachi* stance for left lower limbs ($p = 0.096$) and right lower limbs ($p = 0.069$) (Table 2).

It was demonstrated that in the *zenkutsu dachi* stance the lateral medial GRFs were statistically significantly higher than the forces measured in the *kokutsu dachi* stance for left lower limbs ($p = 0.01$) and right lower limbs ($p = 0.007$). The differences in these forces between the left lower limb in *zenkutsu dachi* and the right lower limb in *kokutsu dachi* ($p = 0.018$) and right lower limb in *zenkutsu dachi* and left lower limb in *kokutsu dachi* ($p = 0.004$) were also statistically significant.

In the *kokutsu dachi* stance, anteroposterior GRFs of the right front leg were statistically significantly higher than in the case of the left leg in the *zenkutsu dachi* stance ($p = 0.033$) and than in the case of the right leg in the *zenkutsu dachi* stance ($p = 0.023$). Even though in the anteroposterior plane the highest values were observed in the *kokutsu dachi* stance, special attention should be paid to the values obtained in the *kiba dachi* stance because the lower limbs in this stance are positioned sideways in relation to the direction of the movement of the athlete (see Table 1).

Table 2. Mean and SD values of the relative GRFs of the left (L) and right (R) front leg in basic stances.

Indicator	Lower limb	zenkutsu dachi	kokutsu dachi	kiba dachi
		F [N/kg]		
Vertical component (F_Y)	L	31.7 ±9.1[e]	28.1 ±5.4	24.1 ±3.9
	R	33.4 ±8.2[c,f]	30.7 ±10.2	25.5 ±8.0
Lateral component (F_X)	L	4.6 ±2.3[a,b]	2.6 ±0.9	4.1 ±1.3
	R	4.7 ±1.6[a,b]	2.7 ±0.9	4.1 ±1.7
Anteroposterior component (F_Z)	L	9.7 ±3.0[d]	12.4 ±3.9	10.7 ±2.5
	R	9.5 ±2.9[d]	13.7 ±4.7	10.1 ±3.8

Significant differences ($p<0.05$) between the GRFs of the left and right lower limb in basic stances: a) from F_X – left limb – *kokutsu dachi;* b) from F_X – right limb – *kokutsu dachi;* c) from $F_{Y\_}$ left limb – *kiba dachi;* d) from F_Z – right limb – *kokutsu dachi*. Tendency towards significant difference: e) from F_Y – left limb – *kiba dachi;* f) from F_Y – right limb – *kiba dachi*.

Out of the 15 Shotokan karate athletes examined, four scored abnormally in the Foot Posture Index Test. In all cases the deviation was symmetrical in both feet. Two athletes were diagnosed with excessive supination (athlete A scored −3p; athlete B scored −2p) and two athletes were diagnosed with excessive pronation (athlete C scored +7p; athlete D scored +9p).

Case analysis showed that athletes with excessive foot supination obtained statistically significantly lower values in the anteroposterior component of the GRF for the *kokutsu dachi* stance. In the case of athlete A this force for the right lower limb was 9.8 N/kg ($p = 0.012$); a tendency to statistically significantly lower values of 10.3 N/kg ($p = 0.08$) was observed for left lower limb. In the case of athlete B this value was 9.5 N/kg for the right lower limb ($p = 0.008$); for left lower limb it was 8.2 N/kg ($p = 0.005$). The mean value of the anteroposterior component of the GRF for the group with a correct FPIT score was 14.6 N/kg for the right limb and 12.8 N/kg for the left limb.

Athletes with excessive foot pronation are characterized by a statistically significantly higher relative value of GRFs for the right lower limb in the anteroposterior plane. In the *kiba dachi* stance the result of athlete C was 12.8 N/kg ($p = 0.026$), while the result of athlete D was 13.5 N/kg ($p = 0.01$) in relation to the mean value for the group with correct foot shape, i.e., 9.5 N/kg.

The data presented in Table 3 shows that not all athletes had symmetric muscle contractures. The Thomas test showed the occurrence of contractures of the rectus femoris muscle (93% right; 87% left). The percentage of the occurrence of hip abductor contractures in the examined group was different. Depending on the functional test used, the results were as follows: Thomas test: 40% right, 53% left; Ober test: 33% right, 40% left. The occurrence of hip adductor contractures was 60% for the right leg and 73% for the left leg according to the Patrick test.

Moreover, in the *zenkutsu dachi* stance in athletes in whom the Ober test showed muscle contractures of the right limb, significantly higher relative median values of the GRFs for the anteroposterior component were found ($p = 0.024$). Moreover, in the *kokutsu dachi* stance a statistically significantly higher median value of relative GRF for the left lower limb for the anteroposterior component was achieved by the group of athletes with rectus femoris muscle contractures ($p = 0.034$) and the group with hip abductor contractures ($p = 0.039$). In addition, in the *kiba dachi* stance, a statistically significant higher median relative GRF for the right lower limb for the anteroposterior component was found in the men with hip abductor contractures in the Thomas test ($p = 0.008$). A similar effect was obtained for the right lower limb and the lateral-medial component in the Ober test ($p = 0.024$).

DISCUSSION

The generated GRFs during the performance of dynamic transitions in basic karate stances are statistically significantly different. In the *zenkutsu dachi* and *kokutsu dachi* stances their vertical components reach values more than 3 times higher than

Table 3. Differences in median GRFs of the lower limbs for athletes with and without muscle contractures.

Stance	Test	Lower limb	GRF	Median (LQ,UQ) n (without contractures)	Median (LQ,UQ) n (with contractures)	p-value
zenkutsu dachi	Ober hip abductor	R	F_z	7.32 (6.85,8.99) 10	11.86 (11.41,12.71) 5	0.024
kokutsu dachi	Thomas rectus femoris muscle	L	F_z	7.48 (6.79,8.17) 2	13.65 (9.92,14.93) 13	0.034
kokutsu dachi	Ober hip abductor	L	F_z	9.70 (8.82,13.65) 9	15.60 (10.35,18.48) 6	0.039
kiba dachi	Thomas hip abductor	R	F_z	8.31 (7.30,8.59) 9	13.28 (10.89,15.21) 6	0.008
kiba dachi	Ober hip abductor	R	F_x	3.45 (2.50,3.78) 10	4.47 (4.11,5.82) 5	0.024

Tests and muscles / muscle groups for which $p<0.05$ were selected. Median (LQ,UQ) n – median (LQ,UQ – lower quartile, upper quartile) number of cases; L/R – left / right limb GRF – ground reaction force component; HAM – hip abductor muscles; RFM – rectus femoris muscle the athletes' body weight. It should also be noted that the human musculoskeletal system is a biokinetic chain, which in consequence causes a strong impact of the feet on the ground, thereby contributing to the loading of the following joints: ankle, knee, hip, and then the spine [21].

Over the years, kata evolved, mainly in terms of the way in which the basic karate stances are performed. Masatoshi Nakayama, taught directly by Gichin Funakoshi, says that the distance between the feet in the *zenkutsu dachi*, *kiba dachi* and *kokutsu dachi* stances should be about 80cm [22]. In practice, the distance between the front foot and the rear foot in the stances depends on the height and skills of a particular athlete [8, 11].

In the *zenkutsu dachi* stance the front knee is bending over, and the backbone is straight. Feet hip-width distance apart. The centre of gravity of the bodyweight is 60% on the front foot and 40% on the rear foot [22]. Comparison of the three basic karate stances leads to the conclusion that in this stance the lower limb is most loaded, which is analogically reflected in the highest value of the vertical component. The study shows that the occurrence of muscle contractures of the thigh abductor muscles leads to an increase in the GRFs in all three components. Therefore, it is important to pay attention to stretching these muscles in order to minimize the loading.

In the *kokutsu dachi* stance it is necessary to bend the knee of the rear leg. The front leg should be projecting forward. The angle between the feet should be close to the right angle. According to the research from 2019, in this position the athlete must maintain an ankle distance of maximum 91 cm for seniors [23]. Body weight distribution: 70% resting on the rear leg and 30% on the front leg [22]. The above-mentioned body weight distribution is reflected in statistically significantly lower values of GRFs of the lateral-medial component. The case study conducted within the scope of the study showed that the athletes whose feet are overly supinated show statistically significantly lower values of the anteroposterior component of the GRFs for the back lower limb in the *kokutsu dachi* stance. However, statistically significantly higher values of the anteroposterior component of the relative GRF in the *kokutsu dachi* stance were observed in the group with rectus femoris and hip abductor contractures. Eliminating these muscle contractures should positively affect the stability of this stance.

In the *kiba dachi* stance the knees are bent, and the body weight should be evenly distributed between both feet. To perform a large stride with the knees bent and feet facing inwards, it is necessary to increase the natural scope [11]. The *kiba dachi* stance is considered unhealthy and dangerous [6]. Fortifying the physical body indirectly means that powerful mentality enhances the body's aptitude to exceed its usual capabilities so that the physical body can gather more energy, pointedness, and power, called "kime" [24]. Performing transitions in conditions similar to sports competition in *kiba dachi* stances involves a high risk of overload changes in knee joints. These joints are anatomically adapted to perform mainly hinge flexion and extension movements. Movement in the *kiba dachi* stance takes place with the lower extremities positioned sideways relative to the direction of movement, which is unnatural (see Table 1). The presence of the anteroposterior component is considered to be particularly dangerous, in that it induces an external knee adduction moment. The values of this component exceed the body weight of the athletes. The study shows that athletes diagnosed with hip abductor contractures generated significantly higher values of these forces. This may indicate that these muscles, due to their shortening, are not able to stop a limb during a dynamic transition, which results in a higher amplitude of the centre of gravity displacement.

According to the study, athletes whose feet are excessively pronated are characterised by a statistically significantly higher value of the anteroposterior component of the GRF in the *kiba dachi* stance, which may be indicative of a lower stability of the position in this direction. However, it may be the case that it was 14 and 22 years of training experience, based on repeated dynamic execution of the *kiba dachi* stance, that led to changes in the shape of the feet towards pronation in these athletes. In order to confirm this hypothesis, it is necessary to carry out tests on a higher number of athletes. Studies carried out in Iran have shown that the genu varum can be considered as an effective factor on vertical GRF as predictor factor of musculoskeletal injuries among the karate professionals [25].

The champion of the world (Luca Valdesi) with 178 cm height performs the *zenkutsu dachi* stance with a distance of 103 cm, *kokutsu dachi* with a distance of 97 cm, and *kiba dachi* with a distance of 117 cm. Gaafar proposed a formula for achieving ideal lengths in the stances by considering horizontal and vertical distances that should be taken up for basic postures, taking into account the indicators achieved by the world champion [8]. Unfortunately, the exact height of Masatoshi Nakayama is not known, however, assuming the average height of the Japanese at that time (161 cm) according to the Ministry of Internal Affairs and Communications Statistics Bureau and using the formula proposed by Gaafar [8], we can clearly see that, according to the prevailing trends, he would have to extend the basic stances by 10-33% depending on the stance. The form in which karate stances are executed is undoubtedly reflected in the generated GRFs.

Verification of the GRFs in various sports is a commonly used research method [26, 27]. For comparison, the value of the vertical component during barefoot running is 23.4 N/kg at a speed of not less than 4 m/s [28]. As the speed increases, the vertical component of the GRFs increases; at 6 m/s-1 it is 25 N/kg [29]. According to the study, dynamically performed karate stances significantly exceed these values, reaching average values of maximum vertical component of up to 33.4 N/kg (see Table 2). However, execution of straight punches (zuki) in the front stance (*zenkutsu dachi*) produces a higher impact force than in the natural stance [30], which is indicative of the fact that karate stances significantly increase the power of the punch, which is why they are justified.

It should be emphasized that the assessment of GRFs among shotokan karate *kata* athletes may allow to verify the correctness of their technique. Additionally, it may be a key tool to improve athletes' skills by stabilizing the posture and minimizing GRFs. Results of studies comparing postural control in high-level *kata* and *kumite* karatekas show that *kata* athletes have a smaller sway area than *kumite* athletes [14].

In karate, stretching is predominantly used as part of the warm-up process. It is also used at the end of training sessions to improve and/or maintain flexibility [31]. Awareness of the importance of muscle stretching is very high among athletes practising this discipline. However, this study shows that the percentage of people with functional changes in the lower limbs is very high. Many years of *kata* training in shotokan karate may lead to the occurrence of adaptive changes, therefore, even more attention should be paid to prevention through introduction of cyclic examinations of the musculoskeletal system and application of appropriate training based on the obtained results.

CONCLUSIONS

The occurrence of contractions of lower limb muscles in shotokan karate athletes has a statistically significant impact on the increase in the generated ground reaction forces during dynamic transitions in three basic *kata* stances. Therefore, it is possible to prevent lower limb overload changes by eliminating muscle contractures and optimizing the GRFs by repeating the sequences of *kata* movements using measuring platforms.

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