Skeletal Muscle Oxygenation during the Nagewaza Kakari Exercise in Judo

（柔道の投げ技の懸かり稽古中の骨格筋酸化レベルに関する研究）

Shukoh Haga[1)], Takako Kizaki[2)], Shogo Sato[2)], Tohru Takemasa[1)], Kazuki Ezaki[3)], Kiyomi Ueya[4)], Fumio Aita[5)], Noboru Hashimoto[6)], Junetsu Ogasawara[2)], Takuya Sakurai[2)], Takafumi Hamaoka[7)], Toshihito Katsumura[8)], Tomonobu Sakurai[9)], Hideki Ohno[2)]

[1)]Institute of Health and Sport Sciences, University of Tsukuba,
[2)]Department of Molecular Predictive Medicine and Sport Science, Kyorin University, School of Medicine,
[3)]Faculty of Education, Shiga University,
[4)]Department of Judo Therapist, General Education Center, Teikyo University of Science,
[5)]Prefectural Sowa Technical High School,
[6)]Department of Judo Therapy, Faculty of Health Sciences, Tokyo Ariake University of Medical and Health Sciences,
[7)]Faculty of Sport and Health Science, Ritsumeikan University,
[8)]Department of Sports Medicine for Health Promotion, Tokyo Medical University,
[9)]Faculty of Bio-Industry, Tokyo University of Agriculture,

芳賀脩光[1)]、木崎節子[2)]、佐藤章悟[2)]、武政徹[1)]、江崎和希[3)]、植屋清見[4)]、會田文夫[5)]、橋本昇[6)]、小笠原準悦[2)]、櫻井拓也[2)]、浜岡隆文[7)]、勝村俊仁[8)]、桜井智野風[9)]、大野秀樹[2)]

[1)]筑波大、[2)]杏林大、[3)]滋賀大、[4)]帝京科学大、[5)]総和工業高等学校、[6)]東京有明医療大、[7)]立命館大、[8)]東京医科大、[9)]東京農業大

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ABSTRACT

Many studies have examined oxygen metabolism in skeletal muscle during exercise. The purpose of the present study was to analyze skeletal muscle oxygenation during Nagewaza Kakari exercises in Judo, and to compare the maximal oxygen uptake of this type of exercise with that recorded during heel-raiser exercises and exhaustive aerobic exercises during treadmill running. The subjects were 6 male Judo athletes (mean: 23 years old) who each possessed more than 10 years of Judo experience. Maximal oxygen uptake was measured using a breath-by-breath technique. The Nagewaza Kakari exercises and the heel-raiser exercises were performed for 5 minutes. Muscle oxygenation was measured by near-infrared spectroscopy (NIRS) using an electrode with a detector attached to the middle position of the calf during each exercise. Mean $\dot{V}O_2max$ values were 46.7±2.2 ml/kg/min. The muscle oxygenation levels during the Kakari exercise decreased to the same levels as those at $\dot{V}O_2max$ in exhaustion, and sometimes attained -100 ~ -130% (the muscle oxygenation levels at $\dot{V}O_2max$ were set at -100%), which was slightly lower than that during the heel-raiser exercise. These results suggest that oxygenation levels of skeletal muscle during the Nagewaza Kakari exercise were lower than levels measured during the heel-raiser exercise.

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連絡先： Shogo Sato, Ph.D. Department of Molecular Predictive Medicine and Sport Science,
Kyorin University, School of Medicine, 6-20-6 Shinkawa, Mitaka, Tokyo 181-8611, Japan.
E-mail: satoshogo@ks.kyorin-u.ac.jp

I. INTRODUCTION

In recent sports science research, studies on the peripheral circulatory system and oxygen metabolism in skeletal muscles have drawn much attention. These studies have centered around the ATP re-synthesis involved in skeletal muscle composition during anaerobic exercise, aerobic exercise, or at the point of muscle fatigue.

Near-infrared spectroscopy (NIRS) was developed and put into practical use in studies during oxygenation and hemodynamics in skeletal muscles. NIRS was first applied to organisms by Millikan et al. (1937). Thereafter, Jöbsis (1977) studied the brain and myocardium, then Chance et al. (1988) proved that it was possible to perform non-invasive measurements of blood volume as well as oxygen metabolism in skeletal muscles. In studies on skeletal muscle oxygenation and hemodynamics related to NIRS, Hamaoka et al. (1996) reported that the rate of decline of the oxygenation level (O_2 decline) immediately after exercise provides an adequate evaluation of the oxidative metabolism in peripheral skeletal muscles. Homma et al. (1996) have shown that one can evaluate the oxygen supply and demand associated with exercise intensity in NIRS analyses on arterial blood blockage. Bae et al. (2000) reported that even during maximal anaerobic exercise done using the Wingate method, oxygen in the muscles is used 4 seconds after starting an exercise, and that the oxygen usage of working skeletal muscles ranges from 1.67 μM/sec to 84.7 μM/sec (51 times). That is to say, the energy demand of the aerobic system using oxygen ranges from 0.01 mM ATP/sec at rest to 0.53 mM ATP/sec after 30 seconds, and the oxidative contribution is 48.3% in skeletal muscles during maximal exercise.

There is also a close connection between whole body oxygen consumption and the oxygenation level of local peripheral skeletal muscles (Demarie et al., 2001; Higuchi et al., 2006; Kawaguchi et al., 2001). We studied the effect of high-intensity endurance swimming training on the oxygenation level of skeletal muscles and $\dot{V}O_2max$, which revealed a significant decline in the oxygenation level of skeletal muscles and an increase in $\dot{V}O_2max$ (Haga et al., 2001). Furthermore, Im et al. (2001) took a look at cross-country skiers, and showed that the strong relationship of % O_2 desaturation to whole body $\dot{V}O_2$ may be attributed to O_2 dissociation in the capillary bed of the muscle to meet aerobic energy demand and is independent of blood flow dynamics during cross-country ski skating. However, Chance et al. (1992) studied rowers, and pointed out that the recovery period was important for attaining a desaturation of Hb and Mb in the working muscle capillary system, and that the Hb/Mb resaturation time was an index for O_2 delivery.

However, NIRS has not been used to measure skeletal muscle metabolism during martial arts events, such as the Judo Tai Sabaki (body shifting) technique. Consequently, in the present study we used a speed titration method of training to total exhaustion on a treadmill to determine the $\dot{V}O_2max$ and oxygenation level of skeletal muscles (calf muscles), and simultaneously conducted a combination of typical Judo techniques for an usual match time of 5 minutes. These techniques included the Seoi Nage (shoulder throw), and the Uchimata (throwing an opponent by putting one's leg between their legs), as well as other techniques. In general, aerobic exercise capacity is needed during a Judo match, whereas anaerobic exercise capacity of skeletal muscles, particularly in the calf muscle, is important at the moment of throwing an opponent by Nagewaza. However, it is not yet to be determined whether Kakari Keiko (Kakari exercise), a classical practice of Judo technique where throwing is repeatedly performed, is beneficial in strengthening muscle power and instantaneous force, and is effective for the strength training of calf muscles, compared with other training methods. Previously, we had our subjects perform the frequently used heel-raiser exercise, with the aim of doing a comparative study of the changes in blood volume as well as the muscle oxygenation levels seen in different exercises. The loading of the calf muscle during a heel-raiser exercise would be similar to the loading by Judo techniques with respect to knee flexion and instantaneous force. Therefore, the purpose of the present study was to compare muscle oxygenation levels between Kakari and heel-raiser exercises.

II. MATERIALS AND METHODS

1. Subjects

Our subjects included 6 healthy adult males, 20-25 years of age (average age of 23), who had more than 10 years of Judo experience and dan-ranks of 2-4. **Table 1** shows the physical characteristics of the subjects. Their body mass index (BMI) was more than 25, but as the fat % shows, the body fat mass was low, suggesting that they were not obese. We explained the aim of the research to the subjects and obtained their written informed consent. Experimental procedures were approved by the Ethics Committee of the Institute of Medical Sciences, University of Tsukuba, Japan.

Table 1. Physical characteristics of the subjects

Subjects (n)	6
Age (years)	23 ± 3
Height (cm)	177 ± 5
Weight (kg)	82.5 ± 13.4
BMI (kg/m^2)	26.1 ± 3
%Fat (%)	16.9 ± 5.4

Values represent the mean ± SD.
BMI : Body mass index

2. Measuring the blood volume and the muscle oxygenation levels using NIRS

Using Omron's NIRS (HEO-200, Omron Corp., Kyoto), we attached probes at intervals of 3 cm to the center of the longitudinal axis of each subject's lateral gastrocnemius muscle. We measured oxy-Hb/Mb for the muscle oxygenation level, and total-Hb/Mb for the muscle blood volume.

Before starting each exercise, we set the muscle oxygenation level at rest to 0%, and executed an arterial occlusion through a pressure manchette to conduct calibration in the upright position, then the blood flow was occluded to the level where the muscle oxygenation was lowest and was sufficiently stable to -100% (Haga et al., 1998).

In each exercise, after the attachment of probes, an arterial occlusion was conducted in the upright position for 5-10 minutes, and then the rest levels of the blood volume and the muscle oxygenation were measured. Subjects started each exercise after 15 minutes of loosening the blood flow. After each exercise, the blood flow was re-occluded in the same manner, and then the exercise-ended levels of the blood volume and the muscle oxygenation were also measured.

3. The measurement contents and protocols during each exercise

1) Measuring $\dot{V}O_2max$

We carried out a running exercise until subjects reached total exhaustion using the 5-degree inclined treadmill speed titration method (gradual increases from 120 m/min every 10 m/min). Simultaneously, we measured exhaled gas using the breath-by-breath method (Aeromonitor AE-280, Minato Co., Tokyo) that was established by Åstrand and Radahl (1986). Heart rate was continuously measured per minute using a telemeter (Fukuda Denshi Co., Ltd., Tokyo) during the exercise. The perceived intensity of exercise by subjects was noted using the Borg scale as one of the criteria of $\dot{V}O_2max$.

2) Measuring the muscle oxygenation level in Judo throwing techniques during Kakari exercise

Subjects carried out Kakari exercise for an assumed match time of 5 minutes, and performed their preferred throwing technique at a rate of once every 3 seconds. In these exercises, subjects carried out the 'unbalancing', 'executing' and 'throwing' sequence of moves. That is to say, they lifted their opponent's body, distancing their feet from the floor, until they reached the moment when they would throw their opponent. During our subjects' preferred Kakari exercise throw techniques, we attached a NIRS probe at intervals of 3 cm to the center of the longitudinal axis of the lateral gastrocnemius muscle of the supporting leg, and continued measurements until the exercise ended.

3) Measuring the muscle oxygenation level during the heel-raiser exercise

When Judo athletes throw opponents, about half of the opponents' weight loads to throwers. Therefore, in order to mimic the Kakari exercise, carrying a barbell equal to half their weight on each of their shoulders, subjects carried out a simple heel-raiser exercise at the rate of once every 3 seconds for 5 minutes. We measured the muscle oxygenation level of the calf muscles during this time, and compared to the results during Kakari exercise throws and to those measured during $\dot{V}O_2max$. We also measured the heart rate during this performance.

Kakari exercise and heel-raiser exercise were conducted in the same day; Kakari exercise was conducted at 14:30 and heel-raiser exercise was conducted at 09:30. The measurement of $\dot{V}O_2max$ was conducted before 1 week of Kakari and heel-raiser exercises.

4. Statistical analysis

A student's *t*-test for unpaired samples was used to compare the means. For more than two groups, statistical significance of the data was assessed by analysis of variance. Where significant differences were found, individual comparisons were made between groups using the *t*-statistic and adjusting the critical value according to the Bonferroni method. Differences were considered significant at $P < 0.05$. Data in the text and figures are expressed as the mean ± SD.

III. RESULTS

As shown in Table 2, $\dot{V}O_2max$ was an average of 46.7±2.2 ml/kg/min, and we observed no major differences between subjects. The maximal ventilation amount ($\dot{V}Emax$) was an average of 144±18 l/min, the maximal heart rate (HRmax) was an average of 188±4 beats/min, and the respiratory quotient (RQ) was an average of 1.06±0.07.

Fig. 1 shows each individual's $\dot{V}O_2max$ (as shown in Table 2), and the calf muscle oxygenation level at the time when the total-exhaustion exercise was stopped. At that point, subjects with higher $\dot{V}O_2max$ levels showed a declining trend in the muscle oxygenation level.

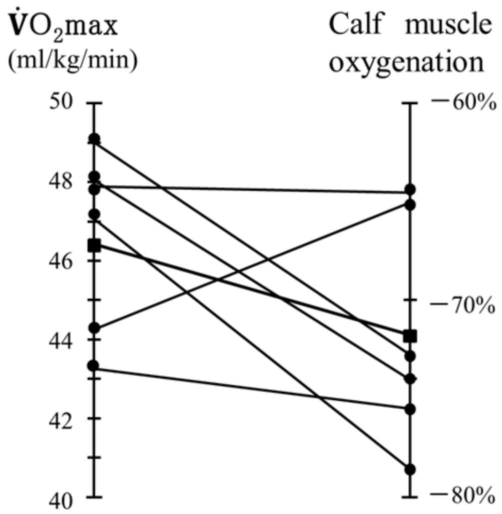

Fig. 1 Calf muscle oxygenation level and maximal oxygen uptake measurement. ●, individual scores; ■, average score.

Fig. 2 shows the variations in muscle oxygenation and blood volume levels for subject D during 5 minutes of the heel-raiser exercise. This shows how the oxygenation level declined until it approximated the ischemic level (−100%), or declined until reaching a level close to that during the exercise.

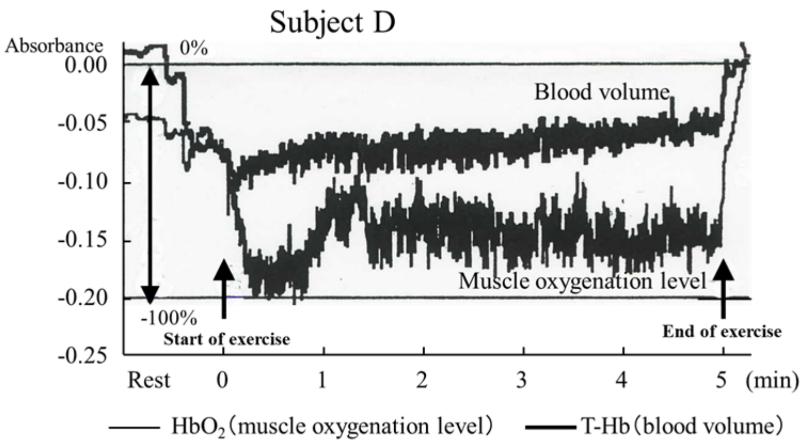

Fig. 2 The variation of blood volume and the muscle oxygenation level in subject D during the heel-raiser exercise.

Fig. 3 shows the muscle oxygenation and blood volume levels during subject D's Kakari exercise. Five minutes after the muscle oxygenation level declined, it was almost equal to the ischemic level. After declining further, the oxygen level increased during the recovery period.

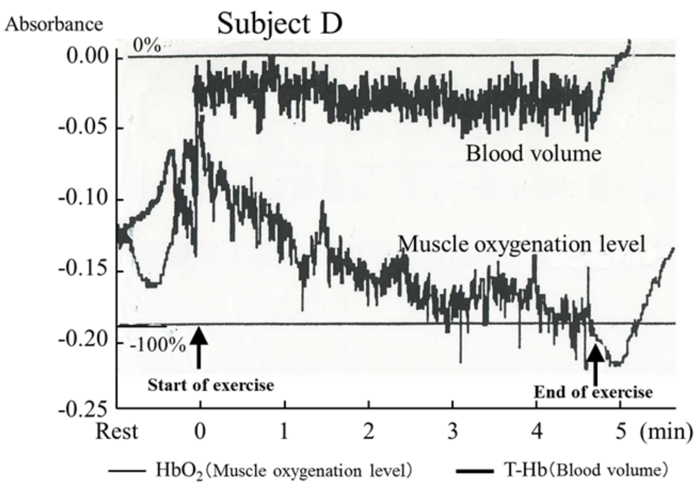

Fig. 3 The variations in blood volume and muscle oxygenation level during subject D's Kakari exercise.

Fig. 4 shows the changes in heart rate during the Kakari and heel-raiser exercises. The Kakari exercise produced a significantly higher score than the heel-raiser exercise, probably due to the fact that large movements were performed to mobilize the entire body's skeletal muscles.

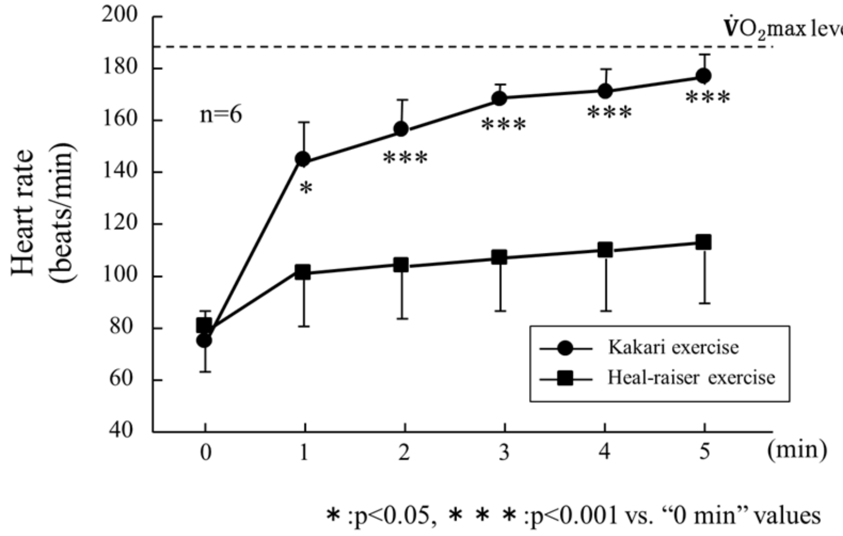

Fig. 4 Heart rate variation during 5 minutes of the Kakari and heel-raiser exercises.

Fig. 5 shows the average score of the muscle oxygenation level for all the subjects when they carried out 5 minutes of both the Kakari and heel-raiser exercises. The heel-raiser exercise had a lower score than the Kakari exercise, but we observed no significant differences between these forms of exercise.

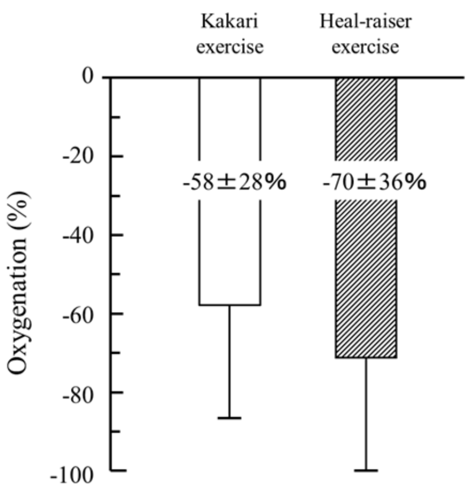

Fig. 5 Comparison of the muscle oxygenation level at maximal oxygen uptake between the Kakari and heel-raiser exercises.

Fig. 6 shows the score when the muscle oxygenation level temporarily reached its lowest point for each subject during the Kakari and heel-raiser exercises. The muscle oxygenation level at rest was set to 0%, and the muscle oxygenation level at $\dot{V}O_2$max was set to -100%. We could see individual differences in the rate of decline in the muscle oxygenation level during both exercises. In subject D, the muscle oxygenation level declined to -110% during the Kakari exercise, and to -140% during the heel-raiser exercise, whereas in subject E, the muscle oxygenation level declined to approximately -130% during both exercises. The average score was -85±28% during the Kakari exercise, and -111±26% during the heel-raiser exercise, respectively.

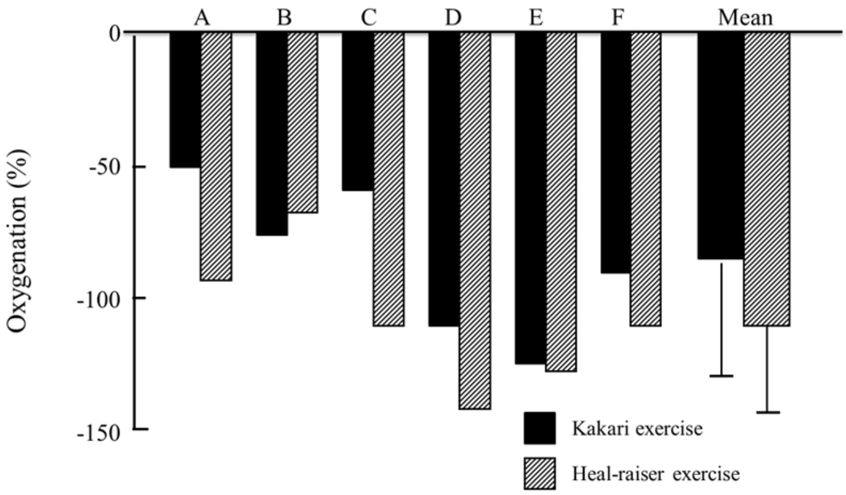

Fig. 6 Comparison of the muscle oxygenation level at the maximum point of decline in regard to the muscle oxygenation level at maximal oxygen uptake between the Kakari and heel-raiser exercises.

IV. DISCUSSION

The subjects of this study were active Judo athletes with *dan*-ranks of 2-4, BMIs showing a somewhat high score of 26.1, but with a fat % that was within a normal range of 16.9%, suggested an increase in lean body mass demonstrating muscle mass size. The high BMI scores of our subjects did not directly interrupt the measurement and value of NIRS, although NIRS is susceptible to the effect of body fat percentages (McCully and Hamaoka, 2000). $\dot{V}O_2max$ was an average of 46.7 ml/kg/min, which was a bit higher than normal, but without taking weight into account this was 3.9-4.0 l/min, which was definitely higher than normal, and seems to indirectly indicate a large quantity of skeletal muscles. The heart rate scores were close to the maximum heart rate predicted by age (220−age), an average of 188 beats/min, suggesting that exhaustion was reached through this full-body exercise.

In contrast, to measure $\dot{V}O_2max$, we applied cuff pressure to the upper part of the lower leg, blocked the blood flow in the muscles, and when complete ischemia was reached, we set the oxygenation level to -100%. Then, we assigned treadmill running to the subjects; as a result, the calf muscle oxygenation levels declined to an average of -72%. The maximum decline was -78%.

During repeated heel-raiser and running exercises, the muscle oxygenation levels declined to almost -70%, whereas in Kakari exercise the average was -58%, thereby suggesting a difference in the amount of skeletal muscle energy metabolism. This kind of discrepancy is thought to affect the muscle oxygenation level via a slight variation in body shifting in the case of practice throws and technique applications. For example, in the case of subject D, the muscle oxygenation level clearly declined during 5 minutes of Kakari exercise, but immediately after finishing the exercise the oxygen demand in the muscles temporarily increased further to -110%, which was lower than the ischemia calibration line of -100%. This shows that the moment the technique is applied, it is possible that the momentary muscle contraction energy metabolism of the calf muscles is occurring at the maximum level. Thus, the average oxygenation level during the Kakari exercise was -58%, but a larger amount of oxygen was used by subjects D (-110%) and E (-130%), which suggests an individual difference.

Since the heart rate was lower during the heel-raiser exercise than during the Kakari exercise (Fig. 4), the heel-raiser exercise seemed to exhibit a lower oxygenation level score. Although the heel-raiser exercise is a very simple movement in this way, Figs 5 and 6 suggest that the muscle contraction is stronger than in Judo moves, and the oxygen demand is higher. In just 30 seconds of a full-power bicycling exercise, oxygen is being used by the muscles 4 seconds after starting the exercise, and the working skeletal muscle oxygen usage is 52.3 times greater than that at rest (Bae et al., 2000). Thus, to improve the competitive potential of Judo, we should not only depend on existing technical practice, but also carry out calf muscle oxygen demand and supply training at a higher level. For example, when engaging in a bike pedaling super-maximal exercise, the heel-raiser exercise with a set level difference, squat exercises, running stairs exercise, climber exercise using equipment, etc., it is necessary to train where the level of the muscle load is even larger than in the Kakari exercise, or to train where a load is persistently applied.

With an assumed match time of 5 minutes, it is important to adopt an interval training method that incorporates anaerobic exercise, or intermittent training that features an increased load on the calf muscles, and to maintain a high oxidative phosphorylation mechanism level for carrying out ATP synthesis in the muscle mitochondria in both short-term and prolonged exercise. In conclusion, muscle loading from the view point of muscle oxygenation levels during Kakarai exercise is thought to be lower than other resistance exercises such as the heel-raiser exercise, which shows that the Kakari exercise, a classic Judo training regimen, is of poorer quality in respect to muscle-strengthening and points out the need to reform the training methods used by Judo athletes.

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