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Research Article

Infrared Thermography-Calorimetric Quantitation of Energy Expenditure in Biomechanically Different Types of *Jūdō* Throwing Techniques. A Pilot Study

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Abstract

The purpose of this pilot study was to investigate the suitability of infrared thermal calorimetry (ITC) for estimating energy expenditure (EE) of two biomechanically different *jūdō* throws, namely, the simple mechanical couple-based *uchi-mata vs.* the lever-based throw *ippon-seoi-nage*, using infrared thermal calorimetry (ITC). Testing subjects included one Caucasian female elite athlete (age: 26.4 years) and one male veteran *jūdōka* (age: 50.8 years). ITC images were captured by an Avio NEC InfRec R300 camera and thermal data obtained were plotted into a proprietary equation for estimation of EE. Data were compared to respiratory data obtained by a Cosmed K4 b2 portable gas analyzer. Oxygen consumption as estimated by ITC capture during practice of *uchi-mata* was markedly lower than during performance *ippon-seoi-nage* in the female (457 mL·min^{-1} *vs.* 540 mL·min^{-1}, $P<0.05$) and male subject (1,078 mL·min^{-1} *vs.* 1,088 mL·min^{-1}, NS), with the difference in values between both genders subject being significant ($P<0.01$). The metabolic cost of the exercise (*uchi-mata vs. ippon-seoi-nage*) itself was 1.26 kcal·min^{-1} (88 W) vs. 1.68 kcal·min^{-1} (117 W) ($P<0.05$) in the female subject, and 2.97 kcal·min^{-1} (207 W) ($P<0.01$) *vs.* 3.02 kcal·min^{-1} (211 W) (NS) in the male subject. Values for the female were significantly different ($P<0.01$) from those of the male subject. The results support the initial hypothesis that the couple-based *jūdō* throws (in this case, *uchi-mata*) are energetically more efficient than lever-based throws, such as *ippon-seoi-nage*. Application of this approach may be of practical use for coaches in optimizing energy-saving strategies in both elite and veteran *jūdō* athletes.

INTRODUCTION

In 1987, Sacripanti after thorough analysis of the physics and biomechanical principles active in *jūdō* throws, concluded that such techniques fall in one of two categories: lever-based *vs.* simple couple-based techniques. Physical lever-based techniques are those techniques where a force is applied with the arms against a fulcrum to complete the throw [1]. An example of such a *jūdō* throw is *ippon-seoi-nage* (back-carrying throw). The second group consists of those techniques that rely on the mechanical principle of a 'simple couple', *i.e.* an acting pair of two bound opposing forces around the opponent's center of mass with the resultant being perpendicular to those forces hence producing a torque. *Jūdō*'s *uchi-mata* (inner thigh throw) is an example of a throwing technique belonging to this second group. Later, Sacripanti, [2] building on earlier findings by Ogawa et al. [3], hypothesized that mechanical couple-based techniques energetically would be more efficient than lever-based *jūdō* throwing techniques [4]. Difficulties in measuring oxygen consumption and energy expenditure in *jūdō*-specific field tests have complicated experimentally investigating this hypothesis. To the best of our knowledge only three such attempts have been made previously [3,5,6].

Measurement of energy expenditure in field studies is subject to a number of well-known challenges [7-10]. Infrared thermographic calorimetry (ITC) represents an alternative to standard indirect calorimetric methods such as open- and closed-circuit spirometry. Although the technique has been in existence for some time [5,6,11,12] its use has not achieved wide distribution in the past. In 2011, Iuliano et al. [14] successfully demonstrated the suitability of infrared-thermographic calorimetry to elucidate the physiologic mechanisms of *t'ai chi ch'uan* (Pinyin: *tàijíquán*). However, recent improvements to the equipment in terms of algorithms, efficiency, and customer-friendliness justify consideration of this technique for evaluation of physiological data in contact sports. In this paper we present a preliminary study in which we use ITC to assess resting energy expenditure (REE) and energy expenditure (EE) during *jūdō nage-komi* (repetitively throwing) drills of *ippon-seoi-nage vs. uchi-mata* in a male and female subject. The purpose of this study was to quantify by means of infrared thermography the differences in energy cost between *jūdō* throws that biomechanically are characterized as lever- *vs.* simple mechanical couple-of-forces-based techniques.

MATERIALS AND METHODS

Subjects

One apparently healthy, nulliparous, Caucasian female elite *jūdōka* (age: 26.4 years, height: 162 cm, body mass: 64.9, *jūdō* experience: 15 years, weight class: <63 kg [note: at the time of the experiment the subject's body mass exceeded her competition weight class limits]) and one apparently healthy, Caucasian male veteran *jūdōka* (age: 50.8 years, height: 170 cm, body mass: 109.1 kg, *jūdō* experience: 39 years, weight class: >100 kg) volunteered to participate in this study. The male subject was a replacement for another male subject who was body mass-matched to the female subject, but who at the last moment had to drop out. The nature and intent of the experiment were carefully explained and the subjects provided their informed consent. The project was approved by the University of Rome "Tor Vergata", and all procedures were conducted in agreement with the Declaration of Helsinki. The study was not controlled for dietary intake and thermal effects of meals, nor was it controlled in the female subject for menstrual cycle phase.

Experimental Design

Assessment of REE: REE was first predicted using the Harris-Benedict Equation [15]. REE was then measured in standing position to limit changes in energy consumption caused by a change in body position. Ambient temperature was 26.5°C and REE was measured over a 30-minute period.

***Jūdō* repetitive throws (*Nage-komi*) exercise test:** The subjects completed two series of five repetitive *jūdō* throws, the first series consisting of the simple couple-type throw *uchi-mata*, the second of the lever-based throw *ippon-seoi-nage*. Each series was separated by a resting period of 5 min.

Assessment of EE: EE results were obtained using the energy-oxygen consumption equivalent. To derive the mean *jūdō*–specific EE in each exercise test, REE was subtracted from mean total EE recorded during the exercise testing session. The metabolic cost of a single couple- or lever-base throw was then estimated by dividing the exercise testing session by the number of throws performed.

Instrumentation

Thermal data were captured using a NEC InfRec R300 (Avio Infrared Technologies Co., Ltd., Tōkyō) high-performance infrared thermal imaging camera with uncooled focal plane array (microbolometer) detector, operating at a resolution of 0.03° at 30°C, an accuracy of ±1°C at ambient temperatures of 10 to 40°C, 1.21 mrad spatial resolution, a spectral range of 8-13µm, 640×480 thermal image pixels, recording at 30 frames·sec^{-1}, and equipped with NS9500PRO software for Microsoft Windows (Figure 1).

The heat of the working muscles produces increases in superficial temperature in a way that is proportional to the amount and intensity of the work. Using an equation that incorporates the radiation energy, the respiration, the evaporation and the energy, the overall energy consumption can be estimated. To achieve this we made use of the equation adapted from work originally performed by Sacripanti [4,5,16-18], and simplified for basic *jūdō* performed in standing position. This equation allows a direct estimation of oxygen consumption from thermographic data:

$$S\sigma\varepsilon F\left(\frac{T_s^4-T_a^4}{t-t_0}\right)+0.06\,n\frac{kS_p\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}}{l_p}\frac{T_i-T_a}{t-t_0}+$$
$$\left\{\begin{array}{l}\left[0.1\varepsilon_h\dfrac{4S^2k\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}}{hl^2}\dfrac{(T_s-T_a)^{1.2}}{T_a^{0.2}(t-t_0)}\right]+\\ \left[0.1(1-\varepsilon_h)\dfrac{4S^2Dc_v\,\mathrm{Re}^{0.8}\,Sc^{0.33}}{hl^2}\left(\dfrac{M_se_s}{RT_s}-\dfrac{M_ae_a}{RT_a}\right)\dfrac{(T_{vs}-T_{va})^{1.2}}{T_{va}^{0.2}(t-t_0)}\right]\end{array}\right\}=\frac{\partial O_2}{\partial t}$$

Using the caloric equivalent, EE was then determined from the estimated oxygen consumption data obtained from the above equation (where S: athlete body surface, σ: Stefan-Boltzmann constant, ε: skin emissivity, F= 0.36, T_s: mean skin surface temperature, T_a: mean environmental temperature, k: thermal conductivity of air, S_p: lung effective surface, R_e: Reynolds number, P_r: Prandtl number, l: subject thoracic diameter, h: athlete's height, P: athlete's body mass, ε_h: the environmental humidity, D: molecular diffusivity of water in air, c_v is the specific heat of water at constant volume, Sc: Sherwood number, $M_{s,a}$: water vapor

Figure 1 Set-up for capturing infrared thermal images during *jūdō nage-komi* (repetitively throwing) drills of lever- *vs.* couple-based throws.

mass, e_s: skin water vapor partial pressure, e_a: environmental water vapor partial pressure, R: gas constant, $T_{va,vs}$: skin and environmental virtual temperature).

Furthermore, in this equation, S indicates the 4π radiating area of the body surface (see [19]) and will vary with posture; the term later was determined with greater accuracy [20] using optical methods and, regardless of stature and body mass, was found to range from 0.70 for a subject in seated position to 0.725 when standing, with a variation of ±2%. When clothing is worn, the radiating area of a body S is increased by a factor F, which corresponds to approximately 15% for each unit of clothing worn [20,21].

In the equation, T_s is derived from the contribution of seven different locations (head, arms, hands, trunk, thighs, legs, feet) multiplied by the relative surfaces, in accordance with earlier observations [22-24]. Local temperatures were measured by fifteen copper-constantan thermocouples and compared with ITC data. Both methods gave very similar results with variation between the two generally being in the 1-2% range.

The potential shielding effect of the *jūdōgi* has been extensively dealt with elsewhere (see [6]. The equation was validated in *jūdōka* against measurements obtained in a (4.5m x 2.5m x 2m) UC2712 environmental chamber (temperature range: -20°C to 75 °C, relative humidity range: 20%-90%) at *Ente per le Nuove tecnologie l'Energia e l'Ambiente* (ENEA), Rome, Italy. To do so, inside the environmental chamber a *jūdōka* was positioned on a proprietary-built stationary cycle ergometer (see [6]) at 25°C and 30% humidity, equipped with thermocouples and double-weave Mizuno *jūdōgi* (Mizuno Kabushiki-gaisha Ōsaka, Japan) while, simultaneously, temperature registrations were made by ITC. The difference between both methods indicated the necessity of a correction factor in the 9-10% range, in agreement with earlier findings by Funk [25].

With regard to the fixed constants included in the equation, consider that in order to analyze the effect of vapor transfer during evaporation (sweating is 96% of water) of heat and mass transfer processes, the transverse mass flow factor in the liquid evaporation process is small and does not significantly affect heat and mass transfer coefficients. Mathematically expressing a general quantitative relationship is a theoretical challenge. Therefore, to tackle this problem it is accepted to revert to similarity theory using a-dimensional numbers arranged in experimentally tested formulas in order to obtain a general relationship that can be extrapolated to similar cases. From the analysis of numerous experimental data on heat and mass transfer during forced flow of moist gases Nesterenko (cited in [26]) established the following relationships well known in thermal engineering: $Nu = 2+C_1 Pr^{0.33} Re^m Gu^n$ and $Sh = 2+C_2 Sc^{0.33} Re^m Gu^{n'}$, in which Nu is the Nusselt number, Re the Reynolds number, Gu the Gukhman number, and Sh the Sherwood number.

When radiative heat transfer is involved, then the bulk of evaporation will be amplified because of absorption of infrared rays by liquid particles. Therefore, the dimensionless relationship Nu = f (Re, Pr, Gu) should include an additional a-dimensional number, such as the Lebedev number (Le), so that Nu = f (Re, Pr, Gu, Le). However, in the equation as proposed by Sacripanti and utilized by us in this paper, instead we employed a modified Gukhman number so that the a-dimensional relationship in the presence of radiative heat transfer is simplified to: Nu = f (Re, Pr, Gu'), with the original Gukhman number being: $Gu = (T_{sk}-T_a)/T_{sk}$ and the new, modified Gukhman number becoming: $Gu' = (T_{sk}-T_a)/T_a$. In reality though, it appears that heat transfer in the presence of mass transfer exceeds the rate of heat exchange alone, and this both in situations of laminar and tubular diffusive.

To allow cross-validation of the results with open spirometry, subjects repeated the exercise protocol while equipped with a Cosmed K4 b2 (Cosmed, Rome, Italy) light-weight breath-by-breath mobile gas analyzer with a flow meter using a bidirectional digital turbine an optoelectric reader with linear response, a galvanic fuel cell (GFC) oxygen gas sensor (range 7–24%), and an infrared non-dispersive thermostatically controlled carbon dioxide sensor (range 0.0–8%). The device was equipped with a portable transmitting unit fixed to a chest harness, and a receiving unit (Figure 1). The accuracy and reliability of the equipment have been previously validated [27,28]. Ventilation ($\dot{V}E$), oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were sampled every 15 seconds, and respiratory quotient (RQ) and REE were computed from these data by means of the Weir Equation [29]. $\dot{V}O_2$ was determined from $\dot{V}O_2 = \dot{V}E \times \left(FiO_2 - FeO_2\right)$ with FiO_2 and FeO_2 being the respective inspired and expired oxygen fractions.

Both the thermal imaging camera and the portable gas analyzer were calibrated before each test protocol; for the portable gas analyzer, this procedure included its turbine flow meter being calibrated using a 3-liter precision syringe (Hans Rudolph, Inc., Kansas City, MO). The subject was also equipped with a lightweight wireless heart rate monitor (Polar Favor, Polar Oy, Kempele, Finland) to register heart rate (HR). Ambient temperature during the exercise tests ranged between 23.6°C-24.4°C, with relative humidity being 53%.

Statistics

The present study was a pilot project with a minimal number of subjects intended to bring an innovative method to the attention of other researchers, against the background of a typical research question that is in need of such method. The study's limited scope did not include the extrapolation of its results to a large population. Normality of data was assumed. Data points were obtained using multiple pieces of equipment (gas analysis, ITC) during the same experiments to answer the same question (EE) in a female and male subject. Successive observations in a time series tend to be correlated and thus serially dependent, which would allow prediction of a value for a certain parameter at a given time from knowing the value of that parameter at another time. Therefore, the various time series were processed as separate and independent series, and analyzed by the corresponding independent test procedures. Ratios of physiological responses were evaluated by analyzing the magnitude of absolute and relative changes during from resting values. Values recorded by the Cosmed K4 b2 analyzer for the two different throws were compared by unpaired sample t-test, as was done for both series measured by ITC. The average value for the corresponding time interval collected by ITC and by the Cosmed K4 b2 analyzers were compared using paired sample t-tests. Measurement accuracy was assessed by calculating the intraclass correlation and visually exploring Bland-Altman plots. Values between male and female subject were compared using unpaired sample t-tests. The α-level was set a priori at 0.05. Data analysis was completed using the IBM SPSS Software, versions 13-22 for Microsoft Windows (IBM Software Group [SWG], IBM, Armonk, NY).

RESULTS AND DISCUSSION

Results

Resting Energy Expenditure (REE): REE values as recorded by the Cosmed K4 b2 were 1464 kcal·d^{-1} (*vs.* 1449 kcal·d^{-1} predicted value) for the female subject and 3492 kcal·d^{-1} (*vs.* 2068 kcal·d^{-1} predicted value) for the male subject, respectively ($P<0.01$). REE values estimated from ITC-data were 1836 kcal·d^{-1} for the female subject (Figure 2) and 2544 kcal·d^{-1} for the male subject, and were not significantly different from predicted values.

Cardiorespiratory data: $\dot{V}O_2$ during the *nage-komi jūdō* drills as estimated from ITC-data in the female subject was 1110 mL·min^{-1} or expressed per body mass, 17.6 mL·kg^{-1}·min^{-1}. Oxygen consumption data after allometric scaling were 23.5 mL·kg$^{-0.75}$·min^{-1} or 26.3 mL·kg$^{-0.67}$·min^{-1}. However, the Cosmed K4 b2 reported significantly ($P<0.05$) lower pulmonary values during the same exercise in the female subject were lower with $\dot{V}E$ being 23.4 L·min^{-1}; $\dot{V}O_2$ was 910 mL·min^{-1} or expressed per body mass, 14.4 mL·kg^{-1}·min^{-1}. Oxygen consumption data after allometric scaling were 19.3 mL·kg$^{-0.75}$·min^{-1} or 21.6 mL·kg$^{-0.67}$·min^{-1}. Peak heart rate was 129 beats·min^{-1}.

ITC-estimated $\dot{V}O_2$ during the *nage-komi jūdō* drills in the male subject was 1,991 mL·min^{-1} or expressed per body mass, 20.0 mL·kg^{-1}·min^{-1}. Oxygen consumption data after allometric scaling were 26.5 mL·kg$^{-0.75}$·min^{-1} or 29.7 mL·kg$^{-0.67}$·min^{-1}. Similarly to what we observed in the female subject, the Cosmed K4 b2 also reported significantly ($P<0.05$) lower pulmonary values in the male subject during the same exercise, with $\dot{V}E$ being 24.7 L·min^{-1}, while $\dot{V}O_2$ was 1022 mL·min^{-1}, and $\dot{V}CO_2$ was 800 mL·min^{-1}. HR peak was 118 beats·min^{-1}.

Exercise Energy Expenditure (couple- vs. lever-based jūdō throws): Mean body surface temperatures pre- and post-exercise ranged from 29.9°C-31.0°C (female) and 27.3°C-34.6°C (male). Exercise Energy Expenditure data are provided in Table 1. Oxygen consumption as measured by infrared-thermographic capture during practice of the mechanical couple-based *jūdō* throw *uchi-mata* was markedly lower than during the practice of the lever-based *jūdō* throw *ippon-seoi-nage* in the female (457 mL·min^{-1} *vs.* 540 mL·min^{-1}, $P<0.05$) and male subject (1078 mL·min^{-1} *vs.* 1088 mL·min^{-1}, NS), with the difference in values between both genders subject being significant ($P<0.01$). Values of both subjects are expressed in Figure 3. These data translated into a mean total energy expenditure of 2.28 kcal·min^{-1} or 137

Figure 2 Typical camera image capturing of infrared resting thermal images to estimate REE.

Table 1: Overview of the metabolic cost of the mechanical couple-based *jūdō* throw *uchi-mata vs.* the lever-based throw *ippon-seoi-nage* as evaluated through infrared-thermographic capture.

Variable	*Uchi-mata*		*Seoi-nage*	
	Female (N=1)	Male (N=1)	Female (N=1)	Male (N=1)
$\dot{V}O_2$, mL·min^{-1}	457	1078‖	540†	1088‖
Total EE, kcal·h^{-1}	137	323‖	162†	326‖
Total EE, kcal·min^{-1}	2.28	5.39‖	2.70†	5.44‖
Peak EE, kcal·h^{-1}	–	–	343	315§
Peak EE, kcal·min^{-1}	–	–	4.92	4.51§
Single throw EE, kcal·min^{-1}	1.26	2.97‖	1.68‡	3.02‖
Single throw EE, cal·throw^{-1}	69	148‖	163‡	277‡‖

*Significant difference between both throws: $P<0.05$; *$P<0.01$; Significant difference between both genders $P<0.05$; ||$P<0.01$.

Abbreviations: $\dot{V}O_2$: Oxygen uptake; EE: Energy Expenditure.

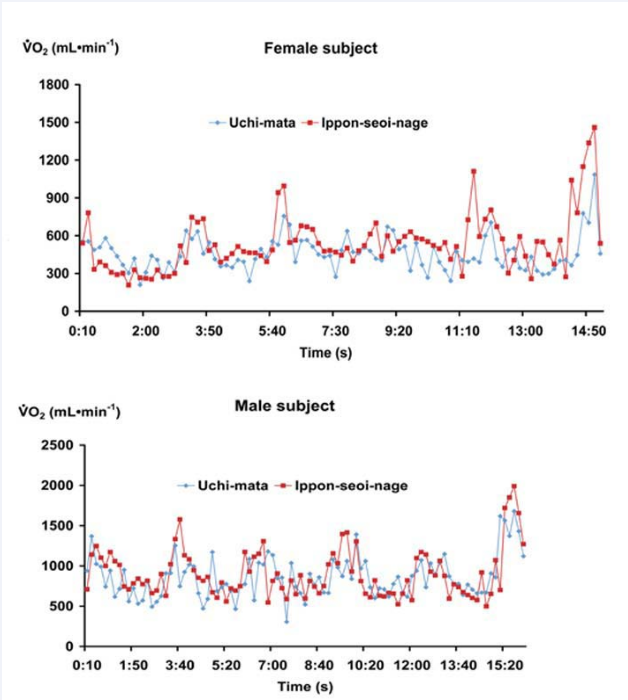

Figure 3 Graphic representation of oxygen consumption data by infrared thermography during two biomechanically different *jūdō* throws (*uchi-mata:* mechanical couple-based throw *vs. ippon-seoi-nage:* lever-based throw) performed in *nage-komi* (repetitively throwing drills) mode. Data for the female subject appear in the top graph; those of the male subject in the bottom graph.

kcal·h^{-1} (159 W) or 3288 kcal·d^{-1} *vs.* 2.70 kcal·min^{-1} or 162 kcal·h^{-1} (188 W) or 3886 kcal·d^{-1} (P<0.05) in the female subject for the selected couple- *vs.* lever-based *jūdō* throws, respectively. In the male subject, this translated into a mean total energy expenditure of 5.39 kcal·min^{-1} or 323 kcal·h^{-1} (376 W) or 7762 kcal·d^{-1} *vs.* 5.44 kcal·min^{-1} or 326 kcal·h^{-1} (380 W) or 7834 kcal·d^{-1} (NS) for the selected couple- *vs.* lever-based *jūdō* throws. The highest energy expenditure measured at any point during the exercise was 4.51 kcal·min^{-1} (315 W) or 6490 kcal·d^{-1} in the female subject *vs.* 4.92 kcal·min^{-1} (343 W) or 7077 kcal·d^{-1} in the male subject (P<0.05).

The average metabolic cost of the exercise itself expressed per unit of time was 1.26 kcal·min^{-1} (88 W) in the female subject *vs.* 2.97 kcal·min^{-1} (207 W) (P<0.01) in the male subject for the mechanical couple-based throw (*uchi-mata*), and 1.68 kcal·min^{-1} (117 W) in the female subject *vs.* 3.02 kcal·min^{-1} (211 W) (P<0.01) in the male subject for the lever-based throw (*ippon-seoi-nage*). When expressed per throw rather than per unit of time, the metabolic cost of the individual throw itself in the female subject was 69 cal or 0.3 kJ *vs.* 163 cal or 0.7 kJ (P<0.01) for couple- and lever-based throws, and 148 cal (0.6 kJ) *vs.* 277 cal (1.2 kJ) (P<0.01) for couple- and lever-based throws, respectively, in the male subject.

Discussion

Contrary to what we observed in the female *jūdōka*, there was a significant discrepancy between predicted REE value in the male *jūdōka* and those recorded by the Cosmed K4 b2, with the measured value being 69% higher than the predicted value. The reliability of the Harris-Benedict and other equations of predicting REE has been previously discussed elsewhere [30,31]. Confounders that may interfere with the accuracy of the prediction are fat-free mass and circulating thyroxine. However, the high value of the REE registered by the Cosmed K4 b2 in the male subject (nearly 3500 kcal·d^{-1}) suggests that other problems may have been involved, and that it is unlikely that the discrepancy is solely on account of the predicted value. These problems are not new, and Littlewood et al. [32] previously reported that Bland and Altman analyses revealed a large mean bias between predicted REE and measured REE using Cosmed K4 b2 data (-194 ± -603 kcal·d^{-1}).

The present study's findings show that infrared thermographic capture of changes in blood flow provides a convenient alternative to pulmonary gas analysis for the estimation of energy expenditure while participating in a rough contact sport activity such as *jūdō*. Since this equipment is not worn on the testing subject's body, it can per definition not interfere with the subject's movements, nor add any addition mass or nuisance. The importance of this finding needs to be considered against the background that most previous studies that contain data about the energy demands of *jūdō* have been obtained from standardized laboratory tests using cycle ergometers or treadmills [33,34]. Extrapolating these data to *jūdō* performance was difficult because *jūdō* extensively makes use of arms, legs and trunk hence yielding higher $\dot{V}O_2$ max values. In 1997, Best & De Crée [35] proposed to overcome these constraints by introducing a portable metabolic analyzer (Cortex MetaMax®,) to provide direct measurements of the metabolic requirements of *jūdō uchi-komi* drills and *randori* in male *jūdōka* [35]. Despite this method representing an important advancement in obtaining pulmonary gas exchange data in *jūdō* athletes during actually relevant *jūdō* exercises, the authors also expressed some reservations due to the frequent detachment of equipment tubing and leads as a consequence of unpredictable, powerful abrupt and explosive *jūdō* movements. A decade later, De Crée [36] showed the suitability of a state-of-the-art portable metabolic gas analyzer (Oxycon Mobile®, Jaeger, Viasys Healthcare GmbH, Hoechberg, Germany) during *jūdō kata* practice [36,37]. However, both studies were limited to male subjects.

In addition, the present study adds operational data on the use of an additional mobile gas analyzer, *i.e.* the Cosmed K4 b2, and its suitability to be utilized in *jūdō* field tests. We encountered no handling problems using the Cosmed K4 b2 irrespective of the gender of the *jūdōka*. We observed that vigorous *nage-komi* drills with the test subject performing the role of *tori* (the one throwing) did not cause the equipment (Cosmed K4 b2 in chest harness) to slip, or its leads to leak or break. Wearing a Cosmed K4 b2 did not significantly interfere with the fluidity of the movements necessary to perform the two different *jūdō* throws (Figure 1). The present study, hence, adds an alternative way to the number of available options to obtain metabolic data during actual *jūdō* exercises instead of laboratory stationary ergometers, and it largely confirms previous findings with yet another portable gas analyzer and in a different type of *jūdō* drill exercise.

However, the applicability of either equipment (mobile gas analyzer *vs.* ITC) is not merely a matter of convenience and comfort, but also a matter of providing accurate and reliable data.

The relatively low values observed for $\dot{V}E$ and $\dot{V}O_2$, as measured by the Cosmed K4 b2 in both the elite female and veteran male *jūdōka*, suggest that the intensity, at which the *nage-komi jūdō* drill exercise was performed by both subjects, was relatively low. This is also suggested by the HR values in both subjects which were only around 120 beats·min^{-1} and nowhere what one could reasonably expect in terms of maximal heart rate. Knowing from previous studies that $\dot{V}O_2$ values during *jūdō* practice at maximal intensity are typically higher than on a cycle ergometer or treadmill [35], the values we observed were somewhat surprising. Much higher values in all these parameters should be the outcome if the *jūdōka* is truly "going all the way" [33,34,38,39], which would be an expectation, at least in the adult elite *jūdō* athletes. Another explanation could involve the accuracy of the equipment. Evaluation of the Cosmed K4 b2 system in previous studies has been inconclusive in terms of its accuracy. However, rather than finding values that were remarkably low, Duffield et al. [40] found the Cosmed K4 b2 to report significantly (P<0.05) higher $\dot{V}O_2$ and $\dot{V}CO_2$ values when compared to either the Cortex Metamax® or to a laboratory metabolic cart during cycle or treadmill exercise. However, Maiolo et al. (2003) found no differences in $\dot{V}O_2$ and $\dot{V}CO_2$ values between the Cosmed K4 b2 and an Airspec QP9000 mass spectrometer. Conversely, McLaughlin et al. [28] observed no differences between the Cosmed K4 b2 and Douglas bag method at rest and high workload (250 Watts), but significant differences (P<0.05) at workloads in between, *i.e.* at 50, 100, 150, and 200 Watts. These authors also found significantly lower $\dot{V}E$ values than those found with the Douglas Bag method, and concluded that the slight overestimation of $\dot{V}O_2$ (50-200 W) combined with the underestimation of $\dot{V}CO_2$ (200 and 250W) by the K4 b2 resulted in significantly lower RQ values at every stage.

To explain the increase in heat dissipation at the end of the exercise (Figure 3), one must realize that thermal flux in and out of the human body is a continuous phenomenon with thermal evolution being much slower than changes in heart rate or oxygen consumption. When one ceases exercise, such as, for example, running, regaining oxygen steady state is a fairly rapid process (minutes). However, regaining thermal steady state takes more than half an hour). When one abruptly ceases exercise, skin surface temperature increases during oxygen recovery, partly because heat dispersion is, approximately, 80% of oxygen input, and because the draught effect caused by freely moving during exercise also suddenly disappears, the effect being especially dramatic during indoor experiments in still air. The increase in skin temperature in still air, however, increases *perspiratio sensibilis* (sweating), finally resulting in an increase of evaporation and heat dissipation. During *jūdō* experiments such as these, at the end of the throwing session, the subjects take off their *jūdōgi* jacket to facilitate further thermal measurements to optimally permit further evaluation of the increases in surface temperature proportional to work done. In comparing the energy expenditure during *jūdō nage-komi* drills of the mechanical couple-based throw *uchi-mata vs*. the lever-based throw *ippon-seoi-nage* our data suggest that, in the female, the lever-based throw was energetically 18% less efficient than the mechanical couple-based throw. In the male subject, the difference was not meaningful, with the couple-based throw being just 1% more energetically efficient than the lever-based throw. These results confirm the initial hypothesis that the couple-based *jūdō* throws (in this case, *uchi-mata*) are energetically more efficient than lever-based throws, such as *ippon-seoi-nage*. If indeed the mechanical couple of forces-based throws are energetically more efficient, then this is likely because they are independent of the friction that lever-based throws are subject to. This is not without consequences for the athlete's performance during contests since the kinetic energy of the athlete will depend on both the oxygen consumption and the athlete's efficiency.

Overall, our observations may be of practical use for coaches in optimizing energy-saving strategies in elite and veteran *jūdō* athletes. Both quantity and quality of the athlete's *jūdō* training are important, irrespective of whether health and general fitness purposes or elite contest-performance are the goal. However, in terms of practical application, it is noteworthy to consider that energetic efficiency is but one parameter in an athlete's quest for victory during a *jūdō* contest. For example, in the long run it may still be more lucrative to attempt a throw that energetically may be somewhat less efficient but that has a higher chance in scoring, than to repetitively having to attempt and fail in successfully applying and scoring with an energetically more efficient throw. Ultimately, the surprise element and the optimization of *debana* [opportunity] and *kuzushi* [unbalancing] may have a proportionally greater impact on the energetic demand of the *jūdōka* than its mechanical foundation.

- In considering the experimental design and results of our study, we are aware of the following limitatioBecause the ITC method was not compared to the Douglas Bag method, which is still the gold standard for pulmonary gas analysis, this pilot study should not be regarded as a true "validation study".
- The authors are aware that in order to have an optimal comparison between male and female subjects regarding the efficiency of different types of throws, the subjects should be matched for body mass and BMI. In this case, unfortunately, beyond the will of the authors a last-moment replacement had to be made due to a drop-out of the original male test subject.
- There is no guarantee that the testing subject mastered the lever-based throw and the simple-couple-based throw he/she performed to the same extent and with the same fluidity and efficiency. That difference in itself may account for any eventual energetic differences observed between performing both throws.
- The choice of specifically what lever-based throw and what simple-couple-based throw to use may cause bias, as it is likely that within the same group some throws will require more energy than others, this depending on the amount of muscle mass that needs to be mobilized, the extent of necessary displacement of the performer and his/her adversary, and whether the chosen throw requires fully lifting the opponent or not. From this limitation the question arises whether the results obtained from measuring a limited number of lever-based or mechanical couple-based throws, can be extrapolated to all lever-based or mechanical couple-based throws.
- Even when assuming that an individual's skill and proficiency in both throws (one lever-based throw *vs.* one simple-couple-based throw) is identical, which of both throws energetically most efficiently can and is applied will likely also depend on the anthropometric characteristics of the opponent, his body position, his skill in blocking off and neutralizing the throw, and how all these factors may affect the degree of modification the performer needs and is able to apply. In the current study, the person who performed the throw and his/her opponent were not first matched for body mass and height.
- These limitations need to be considered in optimizing the design of future larger scale studies to investigate the energetic demands of several other lever-based and simple mechanical couple-of-forces-based *jūdō* throws, before findings can be generalized for all such throws in the same group. Having established the suitability of infrared thermographic equipment in the analyses of changes in blood flow during *jūdō* activity, possible additional applications of this equipment might involve the quantitative energetic determination of the role of individual muscles *i.e.* hotter areas— during *jūdō* movements. Such data may provide further insights optimizing *jūdōka*'s mechanical and energetic efficiency in performing certain throws.

CONCLUSION

Simple-couple throws, such as *uchi-mata*, may energetically be more efficient than lever-based throws, such as *ippon-seoi-nage*. However, it remains difficult to translate this observation into a practical consideration such as whether one technique would have a higher capacity to be effective during a fight than the other. Such conclusion is obscured by significant confounders, such as a *jūdōka* rarely mastering every different technique with the same level of proficiency, and because anthropometric differences with the opponent and specific skills of the opponent may outweigh the net energetic advantage of one technique over another.

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