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Video Biomechanical Analysis of Shoulder Impact Kinematics in Tai-Otoshi and Morote-Seoi-Nage Judo Throws: A Cross-Sectional Study

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Abstract: Background: Shoulder injuries in judo are common as the falling player (uke) lands. Two throws implicated in shoulder injury are tai-otoshi and morote-seoi-nage. Kinematic investigation can provide insight into possible shoulder injury mechanisms and allow for appropriate preventative measures to be suggested. We used two-dimensional (2D) video analysis to measure and compare: (a) the peak acceleration and (b) the peak velocity of uke's shoulder when tai-otoshi and morote-seoi-were performed by elite adult judoka. Methods: Eight male participants were recruited from the Budokwai Judo Club in London, UK. The mean age, height, and weight of participants were 25.4 ± 5.2 years (18–34), 1.7 ± 0.0 m (1.7–1.8), and 75.0 ± 5.2 kg (66–80), respectively. Throws were recorded using an iPhone 6S camera and uploaded onto Kinovea for subsequent processing. Results: The peak acceleration (m/s^2) was greater in tai-otoshi (71.6 ± 12.4) compared to morote-seoi-nage (67.9 ± 9.9), although this was statistically insignificant. The peak velocity (m/s) was significantly greater (p = 0.030) in tai-otoshi (5.1 ± 0.8) than in morote-seoi-nage (4.5 ± 0.6). Conclusions: A greater peak velocity in tai-otoshi suggests that the shoulder is subjected to increased loads upon impact. This may indicate that tai-otoshi carries a greater risk of shoulder injury. Nage-komi (repetitive throwing) practices in training should follow gradual loading principles—beginning with morote-seoi-nage, before moving to tai-otoshi, for example. We must be aware of any assumptions made in estimations of impact force, and future in vivo research is required to provide more definitive values. Meanwhile, coaches must continue to ensure that correct ukemi (breakfall) technique is displayed by athletes before performing throws.

Keywords: injury; mechanism; prevention; acceleration; velocity

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1. Introduction

Judo is a grappling martial art that was created by Jigoro Kano in 1882. Core values of the sport include discipline, humility, and respect [1]. In practice, players attempt to either throw opponents directly onto their back from a standing position (nage-waza) or display control in groundwork via pinfall or submission (ne-waza) [2].

Epidemiological research continues to highlight the considerable risk of injury in judo [2–4]. The shoulder is consistently recognised as a frequently injured site, and a recent publication found that almost 16% of injuries in elite judo competition over a 15-year period were to the shoulder [2–6]. Injuries during judo training are no less common; in fact, it is thought that more injuries occur in training (58%) than in competition (42%) [7]. A player landing after being thrown (uke) is considered the most common injury situation in judo, and two strongly implicated throws include tai-otoshi (body drop) and morote-seoi-nage (two-handed shoulder throw) [2,8,9]. In tai-otoshi, the throwing player (tori) places their hands on the sleeve and lapel of uke's uniform (gi) whilst pulling uke towards them. Tori widens their stance and throws uke over their shoulder with both arms. In morote-seoi-nage, tori drops their feet whilst pulling uke towards them, before loading uke onto their back and throwing them forward with both arms [10,11].

Previous biomechanical analyses of osoto-gari (major outer reap) and ouchi-gari (major inner reap) have helped to further our understanding of head injuries in judo [12,13]. In osoto-gari, tori breaks uke's balance towards their rear corner, then sweeping uke's leg and causing them to be thrown backwards [14–16]. In ouchi-gari, tori first pushes uke backwards, before sweeping uke's leg from the inside with their own leg, causing them to fall onto their back [14–16]. If unable to respond adequately to an attack using osoto-gari or ouchi-gari, uke risks occipital head contact with the tatami (mat) when landing [13,16]. The significant forces generated upon impact can cause severe head injuries [16,17]. Risk factors for head injury from these throws have since been identified, allowing for appropriate preventative measures to be suggested and trialled in subsequent research [18,19].

A similar approach may help tackle the shoulder injury problem. Frequent shoulder injury diagnoses include acromioclavicular (AC) joint sprains, clavicle fractures, and dislocations [3,4]. Current principles of shoulder injury prevention in judo include muscle group strengthening and defensive reactionary movements, in order to avoid withstanding dangerous biomechanical loads [7]. Relevant exercises and practices can be taught to players of all abilities through effective injury prevention programmes, and should be made specific where possible [20,21]. To quantify the potential risk of certain throws, kinematic parameters such as velocity and acceleration can be measured and used to determine load and estimate impact forces [22]. An awareness of this, alongside the biomechanical sequences of high-risk throws, is necessary in order to elucidate possible shoulder injury mechanisms in judo [23]. Altogether, this affords coaches the opportunity to better manage the conditions of training and competition, to lower the risk of shoulder injury [4,24].

The biomechanical mechanisms of head injuries in judo have been examined extensively, although shoulder injuries have been researched in far less depth. The aim of this study was to investigate shoulder impact kinematics in tai-otoshi and morote-seoi-nage, when performed by elite adult judoka. We video-analysed and measured: (a) the peak acceleration and (b) the peak velocity of uke's shoulder during both throws to further our understanding of shoulder injury mechanisms in the sport. The null hypothesis was that there would be no difference in either variable between throws. The research hypothesis was that at least one variable would be greater in tai-otoshi than in morote-seoi-nage.

2. Materials and Methods

2.1. Participant Recruitment

Male and female participants were eligible if they were $\geq$18 years old and reported no current or recent ($\leq$6 months) injuries. It was necessary that participants had attained their first dan (black belt) rank, to ensure throws were executed correctly. This would also minimise injury risk during demonstration. A consultant sports physician and 6th dan judoka was present to medically assess any participants whose eligibility was unclear. Inclusion and exclusion criteria are outlined in Table 1.

Participants were recruited from The Budokwai Judo Club in Chelsea, London, UK. An initial letter was sent to the club which described the study and requested permission to record on site. We asked the club to share this information with members who may be interested and offered our contact details to answer any queries. A minimum sample size of five was calculated with reference to another study video-analysing judo throws [14]. This was made using G*Power (Erdfelder, Faul and Buchner, 1996), with an α value of 0.05 and 80% power [25].

Table 1. Inclusion and exclusion criteria.

Inclusion	Exclusion
	Age < 18 years
Age ≥ 18 years	Non-registered judo players
Registered judo player with first dan rank	Ranking level below first dan
No current or recent (≤6 months) injury	Current or recent injury
	Shoulder pain

Seventeen elite judo players were contacted, of which twelve responded with interest. Four players were excluded due to current or recent injury. Eight male participants deemed eligible were included in our study. The mean age, height, and weight of participants were 25.4 ± 5.2 years (18–34), 1.7 ± 0.0 m (1.7–1.8) and 75.0 ± 5.2 kg (66–80), respectively. Informed written consent was obtained from all participants prior to data collection. The participant recruitment process is represented in Figure 1.

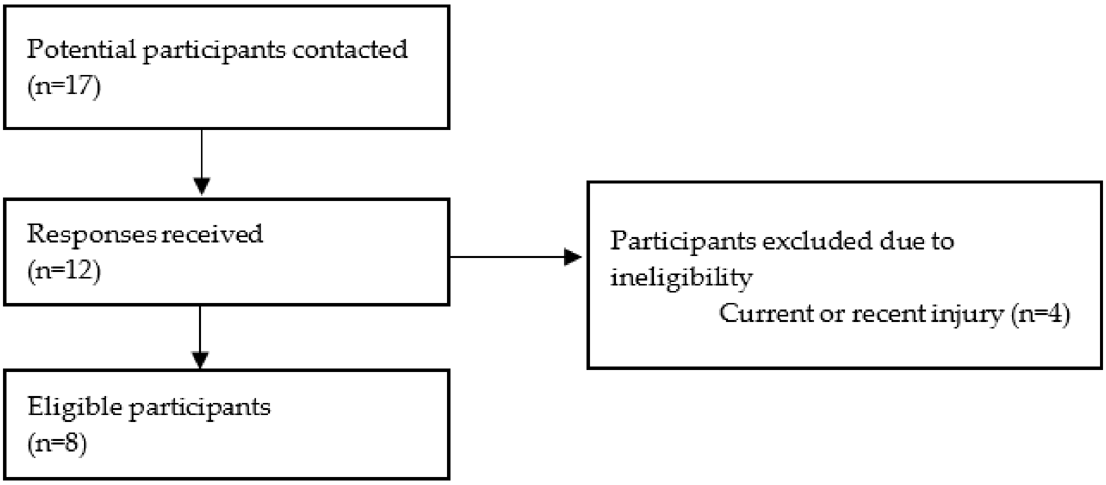

Figure 1. Flowchart representing the participant recruitment process.

Ethical approval for this study was obtained from the Queen Mary Ethics of Research Committee at Queen Mary, University of London (QMREC2014/24/149). This study was conducted in concordance with the ethical standards of the Declaration of Helsinki.

2.2. Data Collection

All data were collected at The Budokwai Judo Club. The tatami (mat) on which throws were performed met specific requirements from the International Judo Federation (IJF) and were identical to those used in competition. Recording took place at the end of training sessions to avoid disruption to scheduling and also ensured athletes were adequately warmed-up. A consultant sports physician was present to treat any injuries that occurred during data collection.

We used two-dimensional (2D) video analysis for the collection and eventual processing of our data. An iPhone 6S with a 12-megapixel camera was used to record all throws. This specification is viewed superior to that of other smartphones and certain digital cameras [26]. The 240FPS (Hz) was preferred over the 30FPS setting to allow for greater accuracy when processing data. The iPhone camera was set up on a tripod at a height of 1.5 m at a distance of five metres from where participants were asked to perform the throws. The tripod was set up such that the camera was 90 degrees facing the participants and this remained stationary for the duration of recording. Participants formed pairs and each performed three tai-otoshi throws, followed by three morote-seoi-nage throws, on one another. A stepwise breakdown of each throw is highlighted in Figure 2.

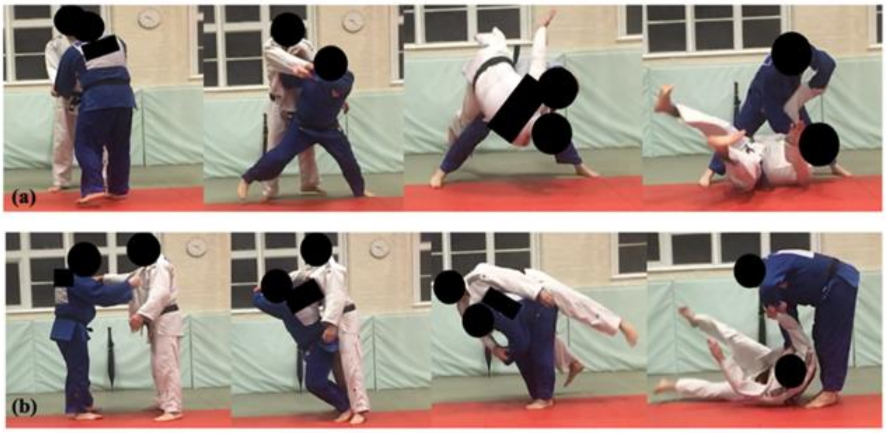

Figure 2. Four-step movement sequence of tori (blue) throwing uke (white) in: (**a**) tai-otoshi and (**b**) morote-seoi-nage.

In the event of an odd number of participants being present during data collection, we would ask another participant to step in to act only as uke. A maximum of one correct practice attempt was offered for each technique and any throw performed incorrectly would be repeated. After each throw, an object of known length was placed vertically at the site of landing for calibration purposes. A maximum rest period of one minute was offered between each throw, unless any of the participants required medical attention. Recording concluded once each participant had performed a total of six correct throws.

2.3. Data Processing

Recordings were uploaded onto Kinovea (version 0.8.15, Roubaix, France) for processing and were trimmed appropriately. Kinovea has been deemed valid and reliable in kinematic assessment, and can accurately measure objects up to five metres away [27].

We tracked the displacement of uke's landing shoulder using Kinovea for the duration of each recording, and this was performed by the same researcher for all throws. A reference marker was adjusted frame-by-frame up to and including the point of impact with the mat. Joint markers could not be used due to the judo gi [28].

Datasets were calibrated and exported to Microsoft Excel and MATLAB (R2020a, Mathworks, Natick, MA, USA) for further processing. A 4th-order low-pass Butterworth filter with zero-lag and a cut off frequency of 15 Hz was applied to reduce statistical noise and smooth data. The first and second derivatives of the smoothed displacement data were taken with respect to time to produce corresponding data sets for the velocity and acceleration of uke's shoulder and recorded: (a) the peak acceleration and (b) the peak velocity of uke's shoulder. We calculated mean values from each participant's set of throws as well as an overall mean and standard deviation.

2.4. Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics (version 25.0, Armonk, NY, USA) and Microsoft Excel. A paired *t*-test was performed to compare the two variables in both throws. A *p*-value of <0.05 was deemed statistically significant. Two-way random intraclass correlation coefficient (ICC) with absolute agreement was used to assess the test–retest reliability. At a 95% confidence interval (CI) estimate, values of <0.5, 0.5–0.75, 0.75–0.9, and >0.9 suggest poor, moderate, good, and excellent reliability, respectively [29]. Cohen's *d* was used to measure effect size, and is described as small (0.2), medium (0.5), or large (0.8) [30].

3. Results

3.1. Acceleration

The average peak acceleration of uke's shoulder in tai-otoshi (71.6 ± 12.4 m/s^2) was higher than in morote-seoi-nage (67.9 ± 9.9 m/s^2) (Table 2). However, the paired *t*-test revealed this to be a statistically insignificant result (p = 0.655). The test–retest reliability of throws was good-to-excellent in both tai-otoshi (0.896; 0.650–0.978; 95% CI) and morote-seoi-nage (0.822; 0.385–0.965; 95% CI). Cohen's *d* revealed a small effect size (d = 0.188).

Table 2. Average peak acceleration and velocity of uke's shoulder in tai-otoshi and morote-seoi-nage.

	Tai-Otoshi	**Morote-Seoi-Nage**		
			p	***d***
Acceleration (m/s^2)	71.6 ± 12.4	67.9 ± 9.9	0.655	0.188
ICC	0.896	0.822		
Velocity (m/s)	5.1 ± 0.8	4.5 ± 0.6	0.030 *	0.783
ICC	0.995	0.759		

* Indicates a statistically significant result ($p < 0.05$).

3.2. Velocity

The average peak velocity of uke's shoulder in tai-otoshi (5.1 ± 0.8 m/s) was higher than that in morote-seoi-nage (4.5 ± 0.6 m/s) (Table 2). The paired *t*-test revealed this to be a statistically significant result (p = 0.030). The test–retest reliability of throws was excellent in tai-otoshi (0.995; 0.984–0.999; 95% CI) and good in morote-seoi-nage (0.759; 0.249–0.946; 95% CI). Cohen's *d* revealed a medium-to-large effect size (d = 0.783).

4. Discussion

In this study, we measured the peak acceleration and velocity of uke's shoulder in tai-otoshi and morote-seoi-nage: two judo throws strongly implicated in shoulder injury. It was assumed that uke applied no conscious resistance when being thrown [28]. Both variables were greater in tai-otoshi than morote-seoi-nage; however, only the difference in velocity showed statistical significance. This suggests that impact loads at the shoulder are greater in tai-otoshi, and we may conclude that tai-otoshi carries a greater risk of injury to judo players.

An increased peak velocity of uke's shoulder in tai-otoshi implies that they are able to be thrown quicker by tori. In tai-otoshi, tori throws uke over their lowered shoulder onto the mat in one swift movement. Conversely, in morote-seoi-nage, tori must first load uke onto their back before they are thrown onto the mat. A study by Ishikawa et al. concluded that the acceleration of uke's head in tai-otoshi was greater than in seoi-nage for similar reasons, and we could apply this to our own findings [12]. It is also worth noting that the peak velocity of uke's shoulder was recorded moments before making contact with the mat in all throws. The velocity at impact would, in theory, become zero, therefore supposing the time difference between the peak and impact velocity to be the same in both throws, a greater change in velocity suggests a greater acceleration. However, given that we did not account for the duration of throws in this study, we cannot say this with confidence. Though, such qualitative analyses might go some way in explaining our results.

Accurately estimating impact forces in the absence of force plates remains challenging. Nevertheless, our findings can be used in theoretical calculations to grossly estimate the impact force. Newton's second law states the force (F) acting on an object is a product of its mass (m) and acceleration (a) [31]. Thus, if the mass of uke's shoulder was known and remained equal in both throws, it is not unreasonable to suggest that impact forces are greater in tai-otoshi. Alternatively, the work-energy principle approximates impact forces when the kinetic energy (KE) and deformation distance (s) of an object during impact is known. Again, this requires the seemingly unrealistic assumption of a constant mass and deformation distance across both throws.

Our data suggests that the shoulder is subjected to greater loads in tai-otoshi, and this may be associated with an increased risk of injury. However, we acknowledge the limitations of our methodology in using our findings to calculate the impact forces, largely due to the absence of other measured variables. We are also aware that additional factors (i.e., landing angle) are heavily involved in shoulder injury mechanisms, although this was beyond the scope of the present study. For this reason, we should be careful when attempting to draw any direct conclusions regarding injury risk, and these factors ought to be accounted for in subsequent research. The study design also meant that we did not consider longer-term injury outcomes, despite no injuries being reported throughout the data collection process. In this instance, it is likely that the elite players included in our study would be familiar with nage-komi (repetitive throwing) exercises in training, and is not associated with a significant injury risk [28,32].

In any case, we should determine the effective mass of uke's shoulder when calculating impact force. The effective mass is a representation of the momentum transfer from tori to uke during a throw, rather than a direct measure of the impacting mass, and is thought to be more accurate in this context [33]. Regression models have been proposed which use individual anthropometric measurements in order to estimate the effective mass and could be utilised as a feature in future research of this nature [34]. Ultimately, we must remember that these are only approximations, and any assumptions made will hold differently in different settings. Alternative means of investigation include three-dimensional (3D) motion analysis, which has been used extensively in similar research and can be advantageous for these purposes [35]. Force plates remain the most accurate means of measuring impact forces, although an inherent issue lies in testing athletes without a mat [36]. More recently, judo-specific ergometer systems have been developed and validated for kinematic assessment but do not reflect the real-life performance of throws [37].

The experience level of participants in this study suggests that throws are likely to have been performed correctly and thus carry minimal injury risk. Proper ukemi (breakfall) technique was also presumed for the same reason. Ukemi is vital in preventing injury by allowing uke to dissipate impact forces when landing. Factors constituting poorer technique are more prevalent at lower levels and athletes must continue to display correct technique before practicing higher-risk throws. A study by Koshida et al. investigated ukemi biomechanics amongst novice players in osoto-gari and identified movement patterns associated with a greater risk of head injury [14]. It would be interesting to analyse ukemi biomechanics in tai-otoshi and morote-seoi-nage moving forward to identify potential risk factors for shoulder injury.

Currently, the British Judo Association (BJA) states that all judo mats must have a minimum thickness of 40 mm to ensure adequate shock absorption [38]. Additional under-mats have been proposed in an attempt to further reduce impact forces when uke lands. A study by Murayama et al. observed significant decreases in head impact force values for osoto-gari and ouchi-gari when an under-mat of 60 mm thickness was used, and it is possible the same would be true at the shoulder [18].

For this study, throws were performed for research purposes, and it is important to consider how our findings may change in a competitive setting. A study by Imamura et al. compared the kinematics of a different throw (harai-goshi) under competitive and non-competitive conditions, in which they found increased velocity of uke secondary and increased throwing power by tori [39]. Increased defensive effort from uke was also detected in competition [39]. Conversely, uke made no attempt to resist being thrown during the collection of our data. Future in vivo measurements would be valuable in order to accurately estimate impact forces.

Players compete at weights of ≤60 kg, ≤66 kg, ≤73 kg, ≤81 kg, ≤90 kg, ≤100 kg, and >100 kg in judo, and these were not controlled in our study [40]. Albeit we are not considering differences between training and competition weights, this might reflect disparities in the strength of participants at the time of recording; particularly given that some consider tai-otoshi more powerful and morote-seoi-nage better suited for shorter players [28]. Though, the practice of judo emphasises maximal efficiency with minimal effort and no trends of this nature were apparent in our findings [1,28].

Our findings are most useful in the context of planning training sessions. Nage-komipractices during training must follow gradual loading principles in order minimise the risk of shoulder injury. For example, this study suggests that nage-komi practices should begin with morote-seoi-nage before tai-otoshi, given the differences in impact kinematics. This also helps to ensure sessions are planned appropriately (i.e., low cumulative load vs. high cumulative load), and players are offered adequate rest periods between training.

Limitations

We acknowledge some limitations of our study. Visual inaccuracies when tracking the displacement of uke's shoulder on Kinovea might have occurred, and this could have affected the subsequent processing of our data. Player fatigue is also a possible confounder as all athletes demonstrated morote-seoi-nage after completing three tai-otoshi throws, and we cannot be certain that this had no effect on our data. Finally, our sample size was relatively small and did not contain any female players.

5. Conclusions

The kinematic analysis of tai-otoshi and morote-seoi-nage revealed a significantly greater peak velocity of uke's shoulder in tai-otoshi. There was no significant difference in the peak acceleration. This suggests that the shoulder is subjected to increased loads in tai-otoshi, indicating that this throw may pose a greater injury risk to players. Critically, we cannot use these findings accurately in estimations of impact force in the absence of other variables, and the effective mass should be incorporated into future impact force estimations. Our methodology did not allow us to identify possible risk factors in shoulder injury mechanisms; however, it offers scope for additional research going forward. In the meantime, it is crucial that players also demonstrate correct ukemi technique before practicing tai-otoshi and morote-seoi-nage.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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