Doctoral Thesis

A biomechanics analysis of the judo osoto-gari technique

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ABSTRACT

Osoto-gari is one of the most popular throwing techniques in modern judo, frequently used in judo matches or practice. According to the Kodokan judo, osoto-gari is regarded as one of the most basic throwing techniques (Kano, 1994; Matsumoto, 1975). Osoto-gari means “large outer reap” in Japanese (Kano, 1994). In osoto-gari, tori (thrower) pushes the opponent’s (uke’s) body by the hands and upper body and simultaneously sweeps the uke’s outside leg, and eventually rotates the uke’s body to fall backward (Daigo, 2005; Imamura & Johnson, 2003; Kano, 1994; Yamashita, 1992).

Little research has been done on the biomechanics of the judo osoto-gari technique, and many mechanisms of the action are still unclear. Most of the judo instruction is often based on intuition and the past experiences of the instructor, and efficient coaching methods with objective data and illustrations have not been established. It makes it hard for judo beginners to master the technique quickly and effectively. In addition, the previous biomechanical analyses of the osoto-gari have mainly focused on head injuries (Hashimoto et al., 2015; Ishikawa et al., 2020; Koshida et al., 2016, 2017; Murayama et al., 2013, 2020; Nakanishi et al., 2021), with less research on the technique itself. The purpose of this study was to biomechanically analyse the judo osoto-gari technique to provide scientific information to the field of instruction.

The thesis consists of five chapters. In chapter 1, I will state the relevance of the biomechanical analysis of osoto-gari and present the purpose of the study. In chapter 2, I will review previous studies that investigated osoto-gari from the biomechanical perspective. Based on the previous findings, two experiments are designed, and specific research hypotheses are presented. In chapter 3, the relevance of the synergistic motion between the upper body and the sweeping leg will be stated based on the kinematic data of black belt and white belt judokas (Liu et al. Sports Biomechanics, 2021). In chapter 4, I will perform kinetics analysis to investigate parameters that are related to the maximum velocity of the sweeping leg. Finally, the general discussion will be given in chapter 5.

The purpose of chapter 3 was to investigate the biomechanical role of the upper body and the sweeping leg in osoto-gari throwing. Twelve black belt judokas who belonged to the university judo team and ten white belt judokas were recruited as a tori. A black belt judoka was recruited as an uke. The tori was instructed to perform osoto-gari at the maximum effort, and the uke was instructed not to resist. Motion data were recorded by a 14-camera motion capture system at 250 Hz, and the ground reaction forces (GRFs) were collected using four force plates at 1000 Hz.

The peak positive angular momentums of the trunk and leg in the black belt were

11.86 ± 2.50 and 30.93 ± 3.16 kg·m^2/s, respectively, which were significantly greater than those in the white belt (5.36 ± 0.68 and 22.79 ± 6.73 kg·m^2/s, respectively). These results suggested that the black belt judokas created a large angular momentum to rotate the uke's body effectively. During the swing phase, the peak angular velocities of the arms and trunk twist in the black belt judokas (-1.98 ± 0.63 and -4.08 ± 0.97 rad/s) were larger than those in the white belt judokas (-1.47 ± 0.42 and -2.52 ± 0.62 rad/s). The timing of the peak angular velocities the of the thigh and shank in black belt were 80.33 ± 5.40 and 90.00 ± 4.41% normalised time, respectively, which were significantly later than those in the white belt group (68.00 ± 7.21; 81.40 ± 5.68% normalised time). During the throwing phase, the peak angular velocities of the arms, upper torso, and trunk twist in the black belt (12.17 ± 5.66; 8.04 ± 4.11; 7.78 ± 3.07 rad/s) were significantly greater than those in the white belt (3.98 ± 1.04; 3.10 ± 0.72; 4.37 ± 1.05 rad/s). Additionally, the difference in the normalised time of the peak angular velocities of the upper torso and trunk twist relative to those of the shank in the black belt group were -8.42 ± 15.29 and -13.42 ± 19.41% normalised time, which were significantly smaller than those in the white belt group (-26.30 ± 11.01; -38.70 ± 25.32% normalised time). These results suggested that the black belt judokas utilize the whole-body coordination to achieve the powerful throw in osoto-gari.

The purpose of chapter 4 was to characterize the supporting leg kinetics during leg sweeping and investigate the relationship between kinetic variables and the sweeping leg velocity at sweep contact in fifteen black belt judokas. During the swing phase, the peak anterior (r=-0.535, p=0.040) and upward (r=-0.579, p=0.024) components of the GRFs generated by the sweeping leg, as well as the peak plantar flexion moment (r=0.548, p=0.034) and power (r=-0.788, p<0.001) of the sweeping leg ankle joint, were significantly correlated with the peak sweeping leg velocity. During the throwing phase, the peak clockwise moment (r=-0.604, p=0.017) was correlated with the peak velocity of the sweeping leg. The peak knee extension moment (r=0.602, p=0.018), hip flexion moment (r=-0.589, p=0.021) and knee power (r=-0.745, p=0.001) of the pivot leg were also strongly correlated with the sweeping leg velocity at sweep contact. The results indicated that exertion of the sweeping leg ankle plantar flexors positively contributes to the sweeping velocity. Additionally, increasing whole-body rotation by contracting the pivot leg knee extensors is a crucial biomechanical factor in accelerating the sweeping leg at sweep contact.

Based on the results of the chapter 3 and 4, the whole body motion of osoto-gari is quantitatively characterized. During the preparation phase, which is said as “kuzushi” and “tsukuri” in the judo term, the relevance of the coordination between the upper and the lower bodies is suggested: the planterflexion torque of the sweeping leg accelerated the body forward and the rotation of the upper body might contribute to pulling and unbalancing the uke’s body. During the throwing phase, which is know as “kake”, the coordination between the knee extension of the supporting leg and rotation of the upper body might contribute to powerful throw of osoto-gari. These results will be expected to be a foundation to establish an efficient instruction for judo beginners.

要約

柔道の投技である大外刈は，試合や練習でも頻繁に施技される足技の一つである．柔道の総本山である講道館では，初心者の習得が容易な「第一教」から高度な技である「第五教」まで 40 本の投技を示している．そのうち，大外刈は施技動作が比較的に簡単であることから，「第一教」に位置付けられている(Kano,1994; Matsumoto,1975)．大外刈はその名のとおり「相手の両足外から大きく片足を振り上げて刈る」ということを意味し，実際に施技する時，足で刈るだけではなく，両手と上半身で働いた押す力と刈足で働いた刈る力を同時に作用させて，相手の体を後方に大きく回転させて押し倒すとされている(Daigo,2005;Imamura & Johnson,2003;Kano,1994;Yamashita,1992)．

これまでの大外刈に関する先行研究は非常に少なく，動作のメカニズムに不明な点が多いのが現状である．また，既存の指導書では各著者の経験則での記述が殆どであり，明確な数字などを用いた解説は見られず，具体性が乏しく，柔道経験が浅い学習者にとってはやや難解な技になるのではないかと考えられる．さらに近年，学校体育における大外刈動作による頭部・頸部損傷等の受傷事故が頻繁に発生したことから，深刻な社会問題として議論されるようになっている．研究者らは大外刈施技動作に関する分析ではなく，頭部が受ける衝撃など，事故防止の方策に重点を置いた研究が顕著に出現している(Hashimoto et al.,2015; Ishikawa et al.,2020; Koshida et al.,2016,2017; Murayama et al.,2013, 2020; Nakanishi et al.,2021)．従って，筆者は大外刈のパフォーマンス向上や技術向上の要因を探るには，全身のメカニズムに着目してバイオメカニクス的手法から研究することが必要

であると考え，本研究に着手した．

本博士論文では，運動学・動力学的な観点から，バイオメカニクス的手法を用いて大外刈を計測・分析し，パフォーマンス向上の技術要因の解明や，初心者指導における科学的アプローチに貢献することを目的とした．

本博士論文は，5 つの章から構成される．第 1 章では，柔道大外刈をバイオメカニクス的に研究することの意義を述べ，本博士論文の研究目的を提示した．第 2 章では，柔道大外刈をバイオメカニクス的に研究した先行研究をレビューし，これまでに得られている知見とこれから研究するべき課題を整理することで，具体的な研究テーマと作業仮説を提示した．第 3 章では，黒帯選手と白帯選手を対象に，柔道大外刈の動作に関する運動学的研究を行い，大外刈における上半身と刈足の連動の重要性を明らかにした．第 4 章では，運動学的解析に加えて，動力学的解析を行い，刈足の最大刈り速度に関連する力学的パラメータを明らかにした．第 5 章では，先行研究の知見や，第 3，4 章で得られた知見を総合的に考察し，大外刈の全身動作メカニズムを明らかにした．

第 3 章では，黒帯選手と白帯選手との比較を通じて，柔道の大外刈における上半身動作のメカニズムを明らかにし，上半身と刈足の連動性を調べることを目的とした．研究の趣旨に同意した黒帯を有する大学柔道部員（以下「黒帯選手」と示す，n=12）および柔道の経験を有する大学生（以下「白帯選手」と示す，n=10）を取（投げる側）の被験者とした．また，受(投げられる側)のみを行う者として，黒帯二段を有する大学生 1 名に依頼した．光学式三次元モーションキャプチャーシステム（カメラ 14 台）およびフォースプレート(4 枚)を用い

て動作解析を行った.測定の際,取は全力で大外刈を行い,受は抵抗せずに投げられるよう教示した.

受の胴体と刈られた足の角運動量(倒れた方向)の最大値は,黒帯選手(11.86±2.50; 30.93±3.16 kg·m^2/s)において,白帯選手(5.36±0.68; 22.79±6.73 kg·m^2/s)と比較して両項目ともに有意に大きかった.これは,黒帯選手が白帯選手より,受の体を力強く回転したことを示している.

スイング局面において,両手および捻転の角速度の最大値は,黒帯選手(-1.98±0.63; -4.08±0.97 rad/s)において,白帯選手(-1.47±0.42; -2.52±0.62 rad/s)と比較して有意に大きかった.刈足の大腿と下腿の角速度の最大値の出現タイミング(規格化時間)は,黒帯選手(80.33±5.40; 90.00±4.41 %Time)において,白帯選手(68.00±7.21; 81.40±5.68 %Time)を比較して有意に遅かった.黒帯選手は,技に入る前に,受の体を強く引き付けながら,刈足の振り上げを遅らせることによって,力をためこんでいることが考えられる.スローイング局面において, 黒帯選手の上半身の角速度の最大値は,両手(12.17±5.66 rad/s),上胴(8.04±4.11 rad/s),捻転(7.78±3.07 rad/s)の三項目において,白帯選手(3.98±1.04; 3.10±0.72; 4.37±1.05 rad/s)と比較して有意に大きかった.上胴と捻転の角速度の最大値の出現タイミングと下腿の角速度の最大値の出現タイミングの時間差(規格化時間)は,黒帯選手(-8.42±15.29; -13.42±19.41 %Time)において,白帯選手(-26.30±11.01; -38.70±25.32 %Time)と比較して有意に短かった.これは,黒帯選手の動作には,刈り動作のみを意識するのではなく,刈足と上半身を連動させて全身の力で投げるという特

徴があることを示しており，大外刈における全身の連動性の重要性を示唆している．

第4章では，黒帯選手(n=15)を対象に，大外刈動作における刈足と軸足のダイナミクスを明らかにし，それらの力学変量と刈足の最大速度との関係性を調査した．測定方法，および被験者への教示は，前章(第3章)と同様であった．

スイング局面において，取の刈足に作用する前方方向(r=-0.535,p=0.040)と垂直方向(r=-0.579,p=0.024)への最大地面反力，足関節の最大底屈モーメント(r=0.548,p=0.034)および足関節の正の最大パワー(r=-0.788,p<0.001)は，コンタクト時における刈足の最大速度と有意な相関が見られた．大外刈は，取からすると前方方向に投げる技なので，予備段階において，刈足が地面を強く蹴ることによって，全身を投げ方向に加速させるための地面反力を発揮しなければならない．それによって得られた身体の運動量を末端部に伝えていき，刈足の刈り速度の増加に繋がるものと考えられる．スローイング局面において，取の軸足に作用する地面反力による重心周りの最大モーメント(r=-0.604,p=0.017)，軸足の膝関節の最大伸展モーメント(r=0.602,p=0.018)の最大屈曲モーメント(r=-0.589,p=0.021)および膝関節の正の最大パワー(r=-0.745,p=0.001)において，それぞれ刈足の最大速度と有意な相関関係が見られた．軸足の膝関節の伸展筋群の活動により，より大きいモーメントを獲得できる．それによって，体幹部を勢いよく前傾し，全身を機能的に連動させて，刈足を速く刈ることが可能となる．

第3,4章の結果から，柔道大外刈の全身動作メカニズムが客観的に示された．柔道用語である「崩し」・「作り」と呼ばれる動作の予備段階において，下半身においては，刈足の足関

節の底屈の活動によって全身を投げ方向へ加速させ, それと同時に, 上半身を投げ方向の反対方向に回転し, 受の体を引き付けていた. 刈足を後方に刈るという「掛け」の段階では, 軸足の膝関節を強く伸ばし, 重心周りのモーメントをできるだけ大きく発揮することと同時に, 上半身の動作を連動させることで, 効果的に大外刈を施すことが可能となると考えられる.

　これらの成果は, 特に初心者に対する大外刈の動作のメカニズムへの理解を高め, 技術のパフォーマンス向上に寄与する有益の知見であり, 柔道指導現場において科学的知見に基づいた指導法を確立するための重要な資料となることが期待される.

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CHAPTER 1

1. INTRODUCTION

1.1. History of judo

Judo is a traditional martial art and combat sport that originated in Japan. Judo was established in 1882 by Jigoro Kano (1860-1938). The word judo can be written with the Chinese characters “柔道”, the *ju* “柔” meaning “gentleness” and the *do* *“*道*”* meaning “principle” or “way”, which can be interpreted as offensive and defensive skills or the way of life. Judo can be traced back to jujutsu, a system of attacking techniques that involves throwing, hitting, kicking, stabbing, slashing, choking, bending and twisting the limbs, defences against these attacks, etc., that was practised and taught widely in Japan during the latter half sixteenth century (Kano,1984). A jujutsu practitioner himself, Kano left out some of the dangerous jujutsu techniques and improved others by making them more practical; then, he added safety, gymnastic, and self-defence elements to attract more people to practice. Initially, judo was considered a self-defence fighting technique, but over time, awareness of its educational value and benefits for developing the physical body and spirit grew.

When judo was first established, there were three fundamental goals of the system that were promoted by Kano: “physical education”, “contest proficiency”, and “mental training”, with the ultimate goal of making the individual a value to society through judo training. Thus, judo is not just a sport but also an educational approach. In 1925, judo was introduced as a regular physical education course in schools and practised and taught systematically (Hamada, 2011).

After founding Kodokan Judo, Kano recognized the importance of spreading and popularising judo overseas. In 1889, he decided to go to Europe and opened a dojo to give judo lectures. As a result, judo slowly began gaining popularity in Europe as a sport, for its philosophy, and as an educational idea promoted by Kano. When the London Olympics were held in 1948 in Britain, the European Judo Federation was founded by judo enthusiasts in Britain, Italy, Switzerland, and the Netherlands. In 1951, the first European Judo Championships were held in Paris, France. In the same year, the International Judo Federation (IJF) was officially established as Argentina and France applied to join. Subsequently, the first World Judo Championships were held in Tokyo, Japan, in 1956. During this period, judo was not well-known worldwide. In the 1964 Tokyo Olympics game, men's judo was recognized as an official Olympic sport. Since then, it has spread rapidly internationally and attracted worldwide attention as a competitive international sport. In the 1992 Barcelona Olympics, women's judo was adopted as an official event. The number of participating countries and athletes quickly increased. Today, in 2022, the International Judo Federation (2007) brings together more than 207 national federations and five continental unions. Thus, it can be said that judo is one of the most popular sports in the world.

At present, at the Olympic Games and World Championships, there are seven weight classes for men and women. To win, an athlete needs to grab the opponent's judo uniform and throw the opponent to the ground, immobilize the opponent's upper body on the ground, or force the opponent to submit with a joint lock or a choke. Therefore, it is necessary to make full use of a variety of techniques to win a match. In addition, with the most recent changes in the rules, the “yuko” decision was revoked, and now competitors tend to try to score an “ippon” point to win the game. As a result, sports are becoming increasingly interesting and elegant. The techniques in modern judo were originally divided into three types: nage-waza (throwing techniques), katame-waza (grappling techniques), and atemi-waza (striking techniques). With the technical and competition system of judo constantly being improved, nage-waza and katame-waza were allowed for confrontation practice and competition; atemi-waza, however, is too dangerous for the practitioner's body and became a part of Kata practice (prearranged forms).

1.2. Importance of biomechanical studies on judo

Since the 1964 Tokyo Olympics, judo, as a traditional Japanese martial art, has rapidly become competitive and internationally recognized. Research has been conducted on various aspects of judo (education, history, physiology, psychology, biomechanics, management, biology, eugenics, etc.) (Matsumoto, 1975; Otaki, 1984).

Biomechanics is the study of human body movements, and biomechanics research mainly uses kinematic and kinetic methods. Kinematics refers to the forms of motion, changes in motion, and the quantitative representation of motion, including linear or angular positions, velocities, and accelerations. On the other hand, kinetics refers to the mechanics of motion, explaining the causes of motion through the quantification of forces and moments acting on the human body. In recent years, biomechanical research methods have been used to analyse various sports motions. As a result, these methods are expected to deepen the understanding of judo throwing techniques and supply new knowledge that is useful for practice and coaching.

Judo is a highly technical combative sport with two active participants; it demands skill, strength, and fitness. Unlike in individual sports such as running, the movements in judo are complex. In particular, throwing techniques include all of the following basic movements: posturing, holding, moving, turning, kuzushi (breaking the opponent's balance), tsukuri (preparing to throw), kake (executing a throw), etc. (Kano, 1986;

Otaki, 1984). These movements are not performed independently; rather, multiple movements must be closely coordinated to achieve optimal throwing performance. All throwing techniques must comply with *Seiryoku-Zenyo* “精力善用”, emphasizing the use of proper techniques and mechanics to achieve maximum efficiency with minimal effort. For these reasons, the throwing techniques are strongly related to laws of mechanics (impulses, momentum, forces, levers, moments of inertia, etc.) and are notably related to performance (Matsumoto,1975; Otaki,1984). Some judo experts point out that the biomechanical approach to research is well suited for the analysis of judo movements and techniques (Imamura & Johnson, 2003; Ishii et al., 2018).

Despite the potential of the biomechanical approach in analysing judo throwing techniques, fewer studies have been conducted on judo than on other sports. According to a literature review by Ishii et al. (2018), research on the biomechanics of judo can be traced back to the 1970s-1990s. However, as the measurement technology was limited during this period, these studies only analysed a few biomechanical variables during the preparation phase of throwing techniques. In fact, these results are of limited help in teaching judo. For that reason, judo instruction is often based on intuition and the past experiences of the instructor, and efficient coaching methods with objective data and illustrations have not been established.

In recent years, the use of three-dimensional motion capture systems and force plates for motion analysis has become mainstream in the field of sports biomechanics, and research on the biomechanics of judo has also progressed considerably. For example, Blais et al. (2007) analysed three-dimensional joint dynamics during the execution of seoi-gari in skilled male judo athletes. Ishii et al. (2008) investigated biomechanical factors that yield fast and skilful execution of the seoi-nage technique by comparing the kinematics of elite and collegiate judo athletes. Deguchi et al. (2016) investigated the linking and coordination of the upper body for executing seoi-gari when the uke was in different positions. Koshida et al. (2016, 2017) studied head injury prevention in osoto-gari. The findings from these studies provided useful scientific knowledge and insight for academic and judo practitioner communities and enabled the establishment of specific guides for coaching, practising, and injury prevention.

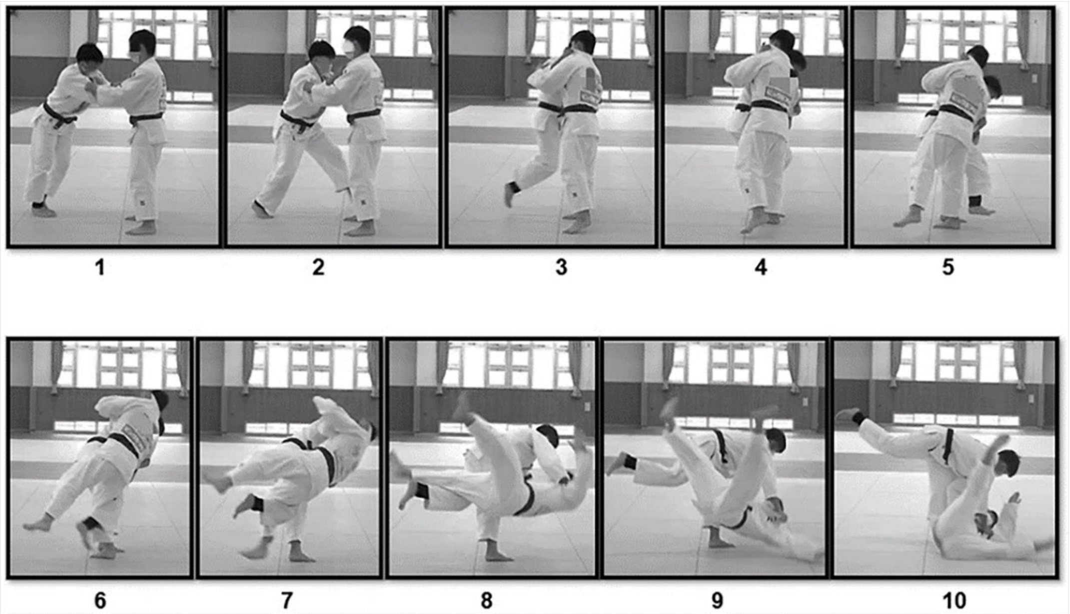

Figure 1-1. Sequence of photographs of osoto-gari. In osoto-gari, the tori (thrower; the one on the left) takes one step forward with the left leg (1-3) and then raises the right leg to prepare to throw (4-5). Finally, the tori sweeps the uke (the faller; the one on the right)'s right leg and pushes his upper body so that he falls backwards (6-10).

Note: In the paper we submitted to Sports Biomechanics (Liu et al. (2021)), the tori's left leg was defined as the lead leg. In this study, the left leg of the tori is defined as the pivot leg, and the right leg is defined as the sweeping leg.

1.3. Osoto-gari (large outer reap)

Osoto-gari is one of the most popular throwing techniques in modern judo. It is very practical and frequently used in judo matches. Osoto-gari, which means “large outer reap” in Japanese (Kano, 1994), is a leg throw technique (as shown in Figure 1-1) in which the tori breaks the uke’s balance, pushes his or her body by the hands and upper body and simultaneously sweeps his or her outside leg out from under him or her, rotating the uke’s body to fall backward (Daigo, 2005; Imamura and Jonhson, 2003; Kano, 1994). The movement is relatively simple and does not require 180-degree rotation of the opponent's body, as does seoi-nage (shoulder throw). Therefore, osoto-gari is considered relatively easy to master and appropriate for beginners (Matsumoto, 1975; Imamura et al., 2006; Almansba et al., 2008). In fact, throwing techniques similar to osoto-gari are popular not only in judo but also in other martial arts, such as wrestling, Russian sambo.

1.4. Purpose of the study

The main purpose of this study was to analyse the osoto-gari judo technique from the kinematic and kinetic points of view using biomechanical methods and to provide useful information for the field of instruction. The first purpose of this study was to investigate the kinematics and selected parameters of the osoto-gari technique performed by practitioners of different skill levels (black belt and white belt judokas) to better understand the upper body action and its relationship to the sweeping leg. The second purpose of this study was to determine the kinetic characteristics of osoto-gari and to investigate the relationship between these kinetic characteristics and the sweeping leg velocity at sweep contact.

CHAPTER 2

2. REVIEW OF THE LITERATURE

The literature review is divided into three main sections. The first is focused on the kinematics of the osoto-gari technique. The second is focused on kinetics. The third is focused on the prevention of head and neck injuries when using the osoto-gari technique.

2.1. Kinematics of the osoto-gari technique

As previously described, the osoto-gari technique is characterized by sweeping of the uke’s outside leg and pushing his or her upper body, causing the uke’s whole body to rotate and fall backward. Therefore, it can be said that effective rotation of the uke’s body is an important mechanical element of the osoto-gari throwing technique. Imamura and Johnson (2003) investigated biomechanical differences in osoto-gari between white belt and black belt judokas. They reported that the peak ankle plantar flexion velocity of the sweeping leg of the black belt judokas was significantly greater than that of the white belt judokas during sweep contact and that the peak angular velocity of the trunk of the uke in the fall direction produced by black belt judokas was significantly greater than that produced by novices. Imamura et al. (2006) analysed the linear momentum of the uke centre of mass (CoM) for harai-goshi, seoi-nage, and osoto-gari in black belt judokas. The results for osoto-gari showed that the anteroposterior components of the uke's momentum indicated forward movement before the tori stepped into the throw, indicating that the black belt judokas pulled the uke's body forward first and then pushed it backward rather than pushing it directly backward. These results indicated that skilled judokas pay more attention to upper body action than novices. These findings, however, do not well reflect the technical characteristics of their upper body actions, an indirect assessment by the uke's behaviour.

The leg sweeping action is also an important factor in the effectiveness of the throw in osoto-gari. Imamura and Jonhson (2003) indicated that the sweeping leg must be executed as an open kinetic chain that sequentially transmits the generated momentum from the thigh to the foot and finally contacts the opponent's lower body. Their study reported that the peak ankle plantar flexion velocity of the sweeping leg in black belt judokas was significantly greater than that in novices during sweep contact. Imamura et al. (2017) reported that the ankle plantar flexion angle of the sweeping leg at sweep contact in black belt judokas was significantly greater than that in white belt judokas. These results demonstrate the benefits of rapid plantar flexion of the ankle joint in the sweeping leg for the execution of the sweeping action, which, from a biomechanical perspective, causes effective transfer of kinetic energy or momentum from the trunk to the foot. However, not all studies support this view. Kuo (2001) compared two styles of leg sweeping in osoto-gari, the knee-flexed style and the traditional knee-extended style. The results revealed that the trunk forward tilt angle and the sweeping force in the former were significantly larger than those in the latter, which indicated that the knee-flexed style might be more efficient and powerful. One possible explanation could be due to judo being a two-person combat sport; for some complex movements, motion assessed in a limited measurement environment cannot entirely explain motion under competitive conditions. Melo et al. (2011) investigated kinematic differences in the sweeping and supporting legs during osoto-gari when throwing ukes of different heights. The results revealed that the angular displacements of the sweeping leg hip and trunk were greater when the tori was throwing a shorter uke during the Kake phase, and the throwing time was shorter with a shorter uke. This study suggests that the physical characteristics of the uke may affect the movement pattern of the tori. Especially for taller ukes, the tori must increase the range of motion of the hip joint of the sweeping leg and of the trunk to obtain a good throw.

2.2. Kinetics of the osoto-gari technique

Nosei et al. (1981) measured the GRF during various judo throwing techniques in elite judokas and analysed the characteristics of the GRF in each phase. Compared to other techniques, osoto-gari showed a higher percentage of anterior/posterior component impulses. Takano et al. (1984) analysed the correlation between the GRF and the knee joint angle for various judo throwing techniques. The results for osoto-gari showed that in skilled judokas, the peak vertical GRF for the supporting leg occurred when the tori was reaping the uke. At the same moment, maximum extension of the knee joint of the supporting leg was also observed. Therefore, it was suggested that rapid extension of the knee is the key to powerful reaping actions. Sasaki and Takahashi (1990) analysed differences in skills among participants at different levels by measuring the distribution of foot pressure in the supporting leg while the other leg was swinging. The study found that foot pressure tended to be focused at the toe in the skilled group, whereas it was closer to the head of the first metatarsal in the unskilled group. In addition, foot pressure was placed on the inside half of the calcaneum in the beginning group. These results indicated that shifting the body weight in a forward direction and concentrating it on the toe might be an important biomechanical factor in osoto-gari during the throw.

The studies mentioned above provide a preliminary understanding of the external forces and pressures acting on the supporting leg in osoto-gari. Although those mechanical parameters may to some extent clarify the osoto-gari technique or offer valuable information for coaching, it is necessary to show the mechanism of the osoto-gari movement by analysing it in greater detail.

2.3. Head injury and injury prevention in osoto-gari

In recent years, injuries and fatalities due to head strikes in judo practice and matches have become a frequent occurrence and have already become a significant problem in the judo community. Osoto-gari, in particular, can easily cause damage to an opponent's head due to the nature of its motion. Therefore, there is much interest in research on the mechanism and prevention of head injuries. Hashimoto et al. (2015) measured the impulsive force on the head when the head was about to touch the tatami following osoto-gari and ouchi-gari throws using motion capture. They reported that the impulsive force on the head of the uke generated by osoto-gari was significantly greater than that generated by ouchi-gari. Koshida et al. (2017) measured the angular momentum on the head during a backward fall in novice judokas in osoto-gari and ouchi-gari. The results demonstrated that the peak angular momentum of the head of the uke generated by osoto-gari was significantly greater than that generated by ouchi-gari. These studies suggested that osoto-gari is more likely to cause damage to the head than ouchi-gari.

To prevent or reduce the risk of head injury in osoto-gari, Koshida et al. (2016) analysed the kinematics of the head and lower limbs when thrown by the osoto-gari technique by comparing experienced judoka and novice. They found that the peak angular momentum of the head of the novice was significantly greater than that of the experienced judoka. Additionally, the angle of the trunk and hip of the novice was significantly greater than that of the experienced judoka. They indicated that novices should strengthen the neck and trunk muscles to suppress the generation of angular momentum in the head, which can greatly reduce the risk of head injuries in osoto-gari.

To confirm whether the use of a mat on the tatami can reduce the impact between the head and the tatami mat when the uke falls backward, Murayama et al. (2013) used a dummy and attached an accelerometer to the dummy's neck to compare two techniques: osoto-gari and ouchi-gari. They also estimated the risk of head injury from the acceleration they observed. The results showed that the risk to the head was significantly smaller in both techniques when using a mat on the tatami.

Summary

In general, little research has been done on the biomechanics of the osoto-gari judo technique. Most studies on the kinematics of osoto-gari separate have performed independent analyses on upper body movements and leg sweeps. However, considering that osoto-gari is a full-body movement that combines upper body pushing with leg sweeping, analysing the linkage and coordination of the upper and lower body may be more meaningful. For the kinetic studies, however, have essentially been descriptive and have not clearly articulated how these mechanical variables influence or affect the mechanics of the osoto-gari technique, such as the execution of leg sweeping or upper body contact. Other judo researchers have preferred to focus their attention on head injuries but not on the technique itself. The osoto-gari technique will be examined from kinematic and kinetic perspectives separately in the chapters that follow. Each chapter will discuss the rationale for studying a particular aspect.

CHAPTER 3

3.1. INTRODUCTION

The osoto-gari technique consists of two main actions: leg sweeping and upper body pushing. While the first action is easy for novices to learn, the second action is hard for even a skilled judoka to master, as it demands that the thrower pull and push the opponent's upper body, putting his or her upper body in a backward leaning position (Yamashita, 1992). Some judo experts (Yamashita, 1992; Daigo, 2005) have stated that the chest-to-chest contact of the two competitor is an important point of the osoto-gari technique, i.e., good chest-to-chest contact can make the opponent lose his or her balance and facilitate an easy throw. Most of their knowledge on the importance of upper body action is based on their intuition and past experiences, which need to be examined by biomechanical research.

A biomechanical study of osoto-gari (Imamura and Johnson, 2003) reported that the peak angular velocity in the fall direction of the trunk of the uke (faller) was significantly greater in the black belt judokas (i.e., a middle-rank judoka) than novices. This result indicated that black belt judokas might pay more attention to upper body action than novices during the throw. Imamura et al. (2006) analysed the linear momentum of the uke's CoM during osoto-gari, showing that the anteroposterior components of the uke's momentum indicated forward movement before the tori (thrower) stepped into the throw. They indicated that the black belt judokas pulled the uke's body forward first and then pushed it backward rather than pushing it directly backward. Although the information provided by these studies highlights the importance of upper body action in osoto-gari throwing, how to perform this action correctly and effectively remains unclear.

The purpose of the present study was to better understand the biomechanical role of the upper body action and its linkage to the sweeping leg in osoto-gari throwing. To this end, we compared the kinematics and the selected parameters between black belt and white belt judokas. The results will provide coaches with practical strategies for teaching osoto-gari execution and will be valuable for non-judo major students to learn and will find a solid base for further study. In this study, we set three hypotheses: (1) The peak angular momentum in the falling direction of the trunk of the uke was significantly greater in the black belt than white belt judokas. (2) The angular velocities of the upper body part would be greater in the black belt than white belt judokas during the throw. (3) The black belt judokas would show a better upper-lower body coordination that would be reflected by simultaneous movements of the leg sweeping and upper-body pushing.

3.2. METHODS

3.2.1. Participants

Twelve male black belt judokas (black belts) (age: 20.3 ± 1.5 years, height: 172.1 ± 4.2 cm, mass: 77.3 ± 8.0 kg) and ten male white belt judokas (white belts) (age: 21.3 ± 1.4 years, height: 173.6 ± 5.6 cm, mass: 71.1 ± 8.5 kg) served as toris (throwers) and participated in this study. The black belt judokas belonged to the university's judo team and had at least seven years of judo experience. The white belt judokas had attended judo classes offered by the university or junior high school and were able to perform an osoto-gari throw. None of the white belt participants had competition or grade test experience. Since the throwing motion can be different depending on the uke (faller), we recruited one black belt male judoka (age: 22 years, height: 173 cm, mass: 81 kg, judo experience: 9 years) to serve as the uke for both the black and white belt judokas (throwers). The height and mass of the uke were average so that all of the participants, including both the black and white belt judokas, were able to throw him. The study's purpose and risks were explained to the participants prior to enrolment, and all participants provided written, informed consent before participating in this study.

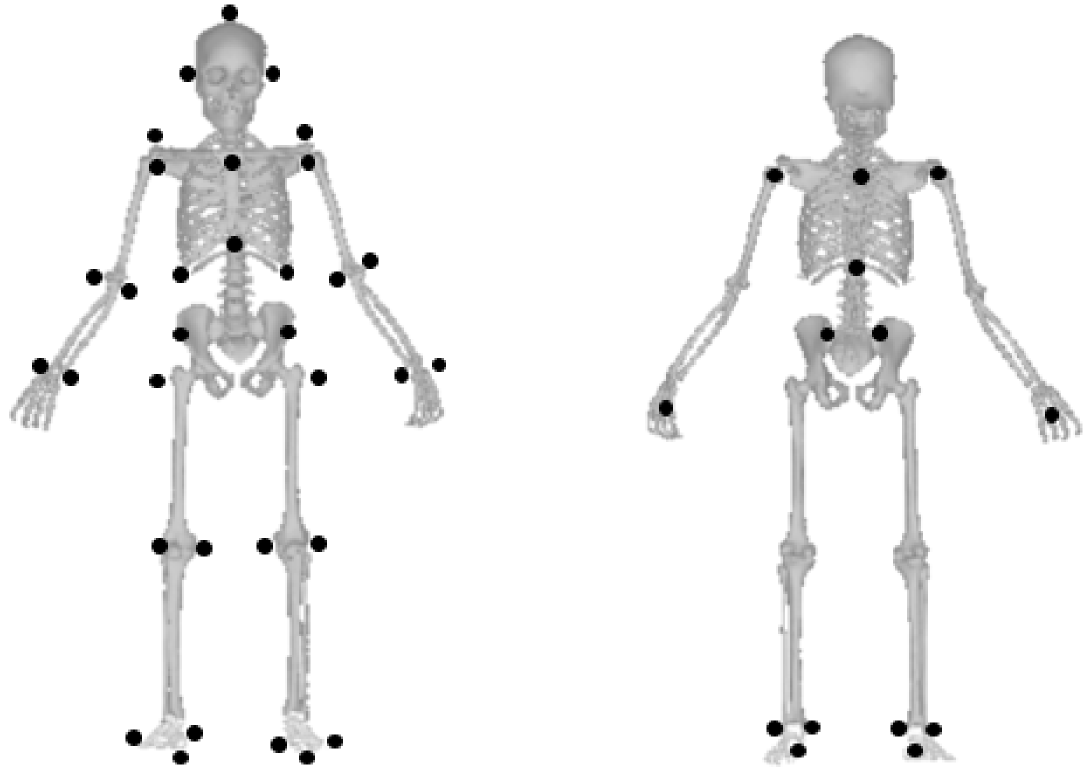

Figure 3-1. Location of the reflective markers

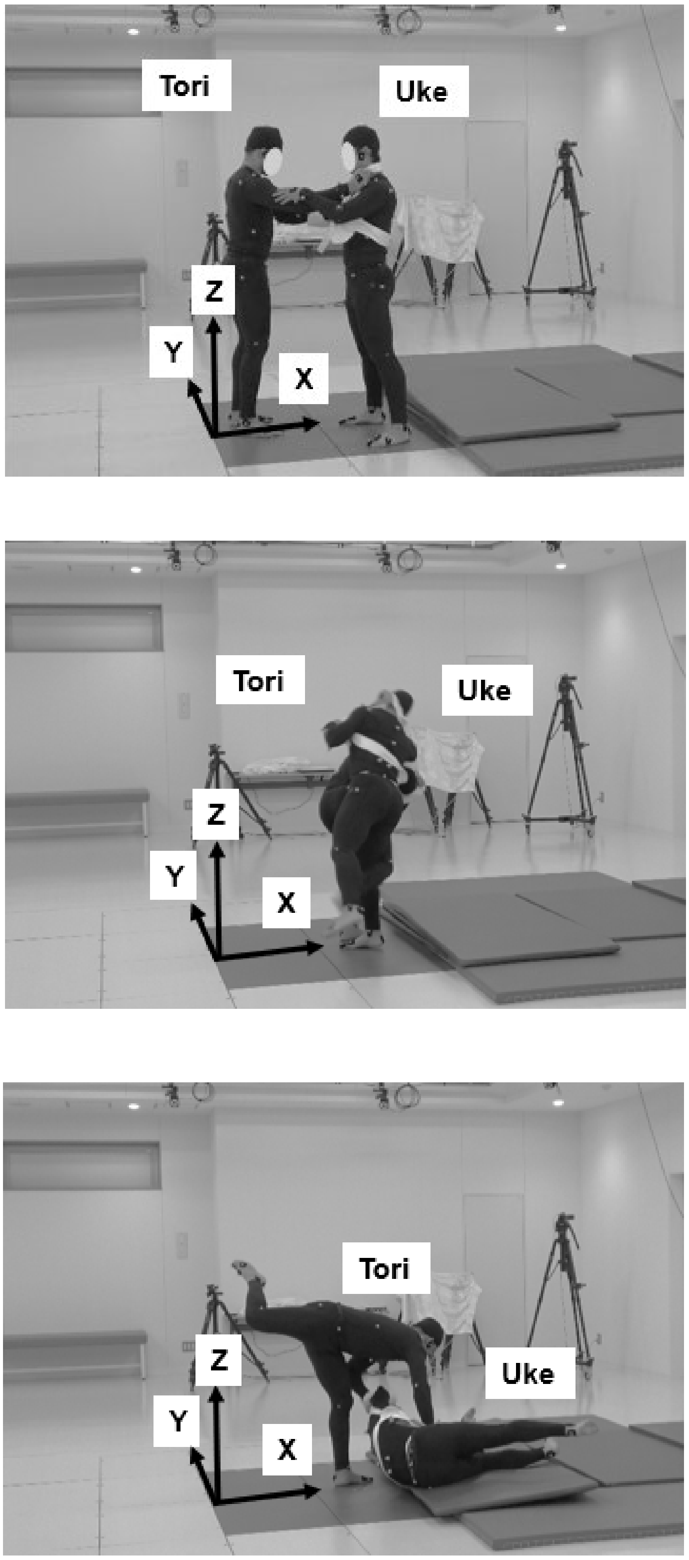

Figure 3-2. Measurement environment

3.2.2. Measurements

The experiment was performed in an indoor biomechanics laboratory. The participants (the tori and uke) wore black sports tights, and 47 reflective markers were placed on the tori and uke's bodies. The location of the reflective markers is shown in Figure 3-1: top of the head, left/right ear, 3rd metacarpal, medial/lateral wrist joints, medial/lateral elbow joints, toes, 1st and 5th metatarsal, calcaneal tuberosities, medial/lateral malleolus, medial/lateral knee joints, greater trochanters, acromial processes, anterior/posterior shoulders, suprasternal notch, xiphoid process, 5th cervical vertebrae, 10th thoracic vertebrae, lateral costal borders (10th rib), anterior iliac spines and superior iliac spines. The participants were allowed to practice osoto-gari in the laboratory to familiarize themselves with the measurement environment before the actual data collection. The uke was asked to wear specially designed judo gear (Figure 3-2) and maintain shizen hontai (i.e., a basic judo posture). We instructed the uke not to resist an easy throw. Every time the tori threw, the tori was asked to rate his performance using a 5-point Likert scale as in Ishii et al. (2018). We instructed the participants to rate the throw as 5 if the trial was as good as their career-best performance. They repeated the trials until two throws with a score of 4 or 5 were successfully captured. When the white belt participants could not reasonably rate their performance by themselves, they were assisted by a university judo coach (coaching experience: 30 years, judo ranking: seventh degree). After the two good throws (score of 4 or 5) were captured, three university judo coaches (coaching experience: 23, 30, and 40 years, judo ranking: sixth, seventh, and eighth degree) independently judged which throw was the best. The trial with 2 or 3 votes was selected as the best performance for each participant and used for subsequent motion analysis.

3.2.3. Data processing

Data processing was performed with MATLAB 2016a (MathWorks Inc., Natick, MA, USA). Three-dimensional marker trajectory data were recorded for the tori and uke using a 14-camera Mac3D motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) with a sampling rate of 250 Hz. The marker trajectory data were filtered using a 4th-order low-pass Butterworth filter with a cut-off frequency of 12 Hz.

The bodies of the tori and uke were modelled as 15 rigid link segments consisting of the head, left/right arms, left/right forearms, left/right hands, left/right feet, left/right shanks, left/right thighs, upper trunk, and lower trunk. The upper trunk and lower trunk were divided by the line connecting the markers placed on the left/right lateral costal borders. The joint centre was calculated using the same method as in a previous study

(Koshida et al., 2016; Koshida et al., 2017). The mass, CoM, and inertial parameters of each segment were estimated using a rigid body model for Japanese athletes (Ae et al.,1992), which was also used in previous judo biomechanical studies (Ishii et al., 2018, Koshida et al., 2016, Koshida et al., 2017).

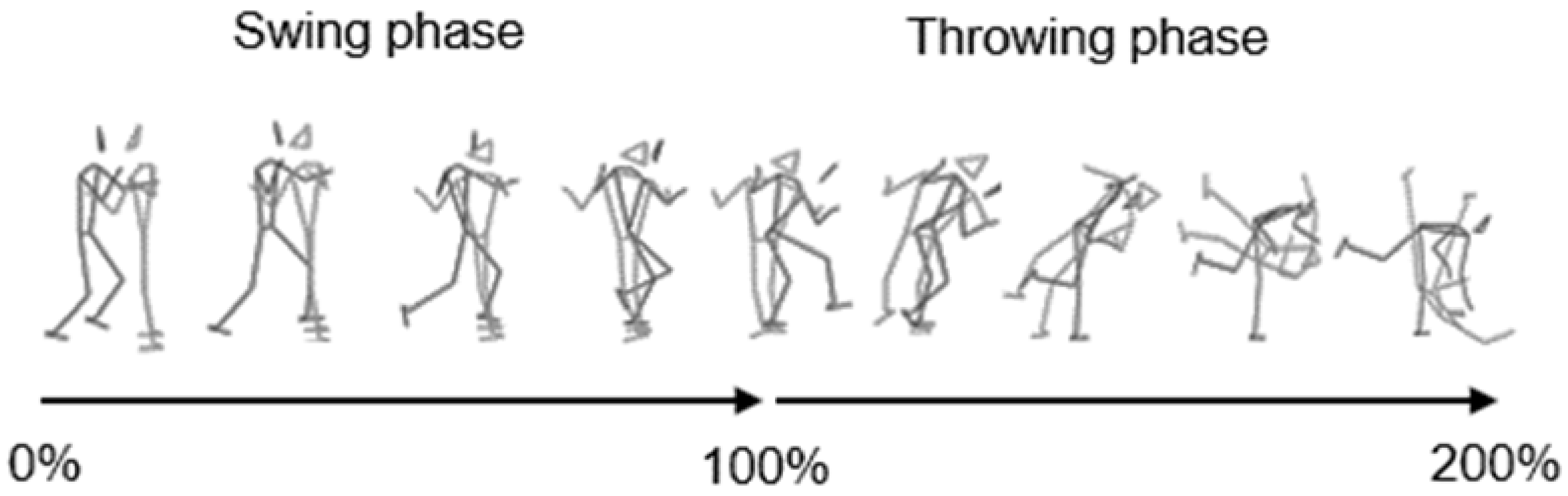

Figure 3-3. Phases of osoto-gari in normalised time.

3.2.4. Phases of osoto-gari

In a previous study, osoto-gari was divided into kuzushi (taking one step forward and raising the sweeping leg), tsukuri (sweep contact to the opponent's lower body), and kake (throwing the opponent’s body on the ground) (Imamura et al., 2006). However, the definition of the phases, especially kuzushi and tsukuri, is not objective and cannot be defined by using kinematic data obtained with a motion capture system. In this study, we defined two phases (Figure 3-3): the swing phase and the throwing phase.

The swing phase started when the tori's pivot leg (i.e., the left foot of a right-handed participant) lifted off the floor, which was identified as when the vertical position of the toe marker was higher than 0.04 cm. The end of the swing phase was defined as when the toe marker of the sweeping leg (i.e., the right foot of a right-handed participant) was at the highest position on the vertical axis. The throwing phase was defined as the end of the swing phase to the instant that any part of the body of the uke was in contact with the judo mat. The instant was confirmed by the GRF data (the threshold value was set to 5 N). All parameters were normalised to 100% of the time of each phase. The left-handed participants were treated as right-handed participants when their data was processed.

3.2.5. Calculated parameters

1) Motion phase time

The motion phase time is an index used to evaluate the tori's osoto-gari performance.

2) Angular momentum of the uke

The angular momentum of the uke is a useful variable for evaluating the effectiveness of the tori's throw. For the calculation, we used the method adopted by Koshida et al. (2016). The formula is as follows:

$$H_{i \to CoM} = [\, r_{i \to CoM} \times (\, m_i \, v_{i \to CoM} \,)\,] + I_i \, \omega_i$$

where $H_{i \to CoM}$ is the angular momentum vector around the CoM of the uke's segment i, m_i is the mass of segment i, and $r_{i \to CoM}$ and $v_{i \to CoM}$ are the position vector and linear velocity vector of each segment i relative to the uke's CoM, respectively. In addition, I_i and ω_i represent the moment of inertia and the angular velocity of segment i, respectively. The segment angular velocity ω was calculated using differentiation for the unit vector (Suzuki et al., 2014). The trunk's angular momentum was defined as the sum of the angular momentum of the uke's upper trunk and lower trunk. The leg's angular momentum was defined as the sum of the angular momentum of the uke's thigh, shank, and foot. Note that the angular momentum of the leg refers to the angular momentum of the leg that is reaped by the tori's leg. The positive and negative values correspond to the falling direction and the direction opposite to the falling direction (the view from the sagittal plane of the uke), respectively.

3) Angular velocity of the upper body of the tori

The arm’s orientation was defined by the angle connecting the CoMs of the right arm and left arm and the Y-axis in the XY plane. The arm's CoM was calculated as the sum of the CoM of the upper arm, forearm, and hand (Figure 3-4). The upper torso orientation was defined by the angle connecting the right and left shoulder markers and the Y-axis in the XY plane. The pelvis orientation was defined by the angle connecting the right and left anterior iliac spine markers and the Y-axis in the XY plane. The trunk twist angle was defined as the upper torso angle difference relative to the pelvis angle (Kageyama et al., 2014). For each angle value, the angular velocity was calculated using the three-point method of numerical differentiation. The positive and negative values corresponded to the forward (i.e., throwing direction) and backward (i.e., opposite to the throwing direction) rotations of the arms, upper torso, pelvis, and trunk twist (the view from the horizontal plane in the tori), respectively.

4) Angular velocity of the sweeping leg of the tori

The sweeping leg was modelled as a two-link kinetic chain comprising the tori's thigh and shank. The segment angular velocity was calculated using the same method as that used to calculate the angular momentum of the uke. The positive and negative values corresponded to backward (i.e., opposite to the throwing direction) and forward (i.e., throwing direction) rotation of the thigh and shank (the view from the sagittal plane of the tori), respectively.

3.2.6. Statistical analysis

In this study, all statistical analyses were performed with JASP 0.14.1 (https://jasp-stats.org/), a free statistical software. The height and mass of the black and white belt judokas were compared using independent-sample Student t test to confirm that the groups were matched in terms of physical characteristics. The normality of the variable was confirmed using the Shapiro–Wilk test; after normality was confirmed, independent-sample Welch t test were performed to compare the motion phase time, peak values and normalised time of the appearance of the peak values in each phase between the two groups. The level of significance was set at $p < 0.05$.

3.3. RESULTS

First, we confirmed that there were no differences in height or mass between the black and white belt judokas (height: $t_{(20)}$ = -0.698, p value = 0.493, Cohen's d = -0.299, 95% CI = -6.05 to 3.02; mass: $t_{(20)}$ = 1.681, p value = 0.108, Cohen's d = 0.720, 95% CI = -1.50 to 13.96).

The motion phase time of the throwing phase for the black belt judokas (0.58 ± 0.08 s) was significantly shorter than that for the white belt judokas (0.72 ± 0.12 s) ($t_{(14.911)}$ = -3.446, p value = 0.004, Cohen's d = -1.502, 95% CI = -0.236 to -0.056). There were no significant differences in motion phase times for the swing phase or total phase between the black and white belt judokas (swing phase: $t_{(16.366)}$ = 0.546, p value = 0.593, Cohen's d = 0.227, 95% CI = -0.114 to 0.194; total phase: $t_{(18.955)}$ = -1.200, p value = 0.245, Cohen's d = -0.504, 95% CI = -0.292 to 0.079), as shown in Figure 3-4.

The angular momentum of the trunk and leg of the uke for both groups increased in the falling direction (+) during the throwing phase (Figure 3-5). The peak positive angular momentums of the trunk and leg in the black belt group were 11.86 ± 2.50 and 30.93 ± 3.16 $kg \cdot m^2/s$, respectively, which were significantly greater than those in the white belt group (5.36 ± 0.68 and 22.79 ± 6.73 $kg \cdot m^2/s$, respectively) (Table 3-1).

The angular velocities of the arms and trunk of the tori rapidly increased in the backward direction (-) at the beginning and end of the swing phase in the two groups (Figure 3-6). The negative angular velocities of the arms and trunk in the black belt group (-1.98 ± 0.63 and -4.08 ± 0.97 rad/s) were significantly greater than those in the white belt group (-1.47 ± 0.42 and -2.52 ± 0.62 rad/s) (Table 3-1), respectively. From the beginning of the throwing phase, the angular velocities of the arms, upper torso, and trunk in both groups were in the forward direction (+) (Figure 3-6). The peak positive angular velocities of the arms, upper torso, and trunk in the black belt group (12.17 ± 5.66; 8.04 ± 4.11; 7.78 ± 3.07 rad/s) were significantly greater than those in the white belt group (3.98 ± 1.04; 3.10 ± 0.72; 4.37 ± 1.05 rad/s) (Table 3-1). Moreover, these peak positive values appeared significantly earlier in the black belt group (146.75 ± 8.80; 143.42 ± 9.33; 148.42 ± 15.15% normalised time) than in the white belt group (156.90 ± 10.98; 160.80 ± 14.00; 173.20 ± 18.91% normalised time) (Table 3-2).

The angular velocities of the thigh and shank in the black belt group increased quickly in the forward direction (-) from the 50% and 80% marks, respectively. The white belt also increased quickly from the 30% and 50% marks (Figure 3-6). The statistical analysis revealed that the peak negative angular velocity of the thigh in the black belt group was -8.12 ± 1.46 rad/s, which was greater than that in the white belt group (-6.26 ± 0.70 rad/s) (Table 3-1). The normalised times of the appearances of the peak values in the black belt were 80.33 ± 5.40 and 90.00 ± 4.41% normalised time, respectively, which were significantly later than those in the white belt group (68.00 ± 7.21; 81.40 ± 5.68% normalised time) (Table 3-2). After that, the values of both variables increased rapidly in the backward direction (+) until the end of the throwing phase (Figure 3-6). The positive angular velocity of the thigh in the black belt group was 6.54 ± 1.21 rad/s, which was significantly greater than that in the white belt group (5.41 ± 1.29 rad/s) (Table 3-1).

Finally, we calculated the difference in the normalised time of the peak angular velocities of the arms, upper torso, and trunk relative to those of the shank in the throwing phase. The differences in normalised time of the upper torso and trunk relative to those of the shank (i.e., defined as the instant of sweep contact shown in Figure 3-5 and Figure 3-6) in the black belt group were -8.42 ± 15.29 and -13.42 ± 19.41% normalised time, which were significantly smaller than those in the white belt group (-26.30 ± 11.01; -38.70 ± 25.32% normalised time) (Table 3-2), respectively.

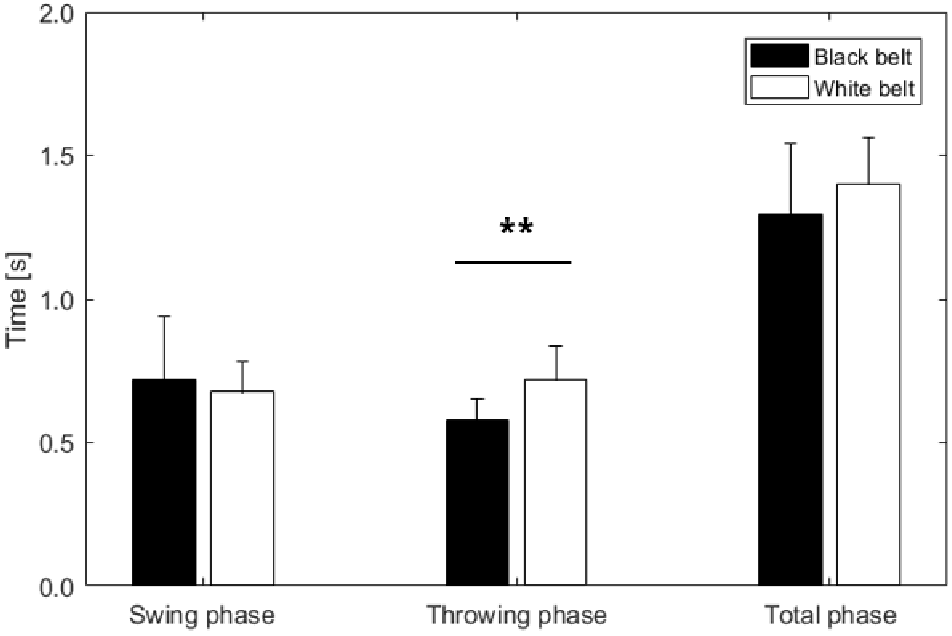

Figure 3-4. Motion phase times (seconds) for osoto-gari thorwing.

Mean ± standard deviation.

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

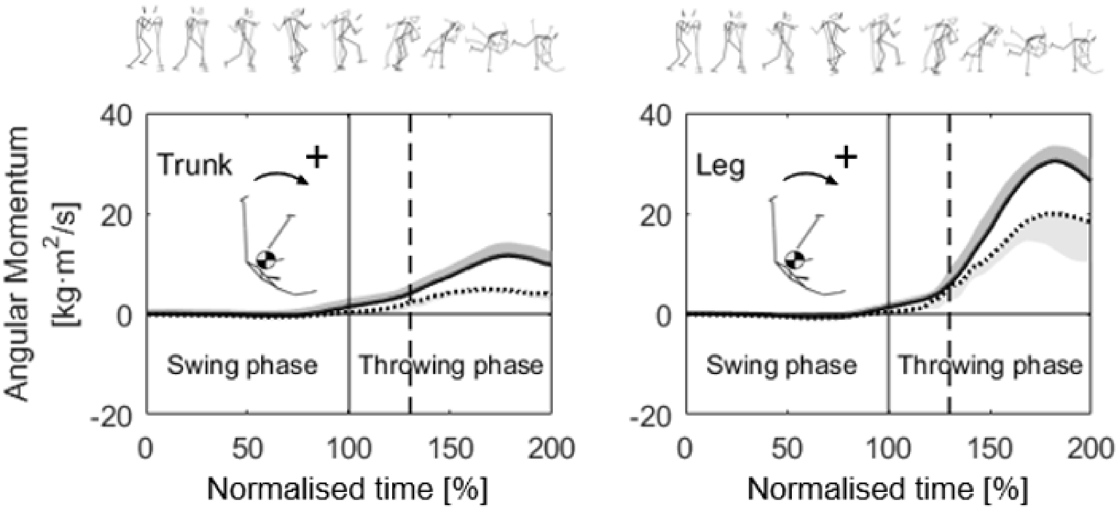

Figure 3-5. Mean (standard deviation) time-series data for the angular momentum of the uke. Solid line: black belt group; dotted line: white belt group; vertical dashed line: instant of sweeping leg contact. The fill for the standard deviation of the positive direction represents the standard deviation of the values for the black belt group, and that for the negative direction represents the standard deviation of the values for the white belt group.

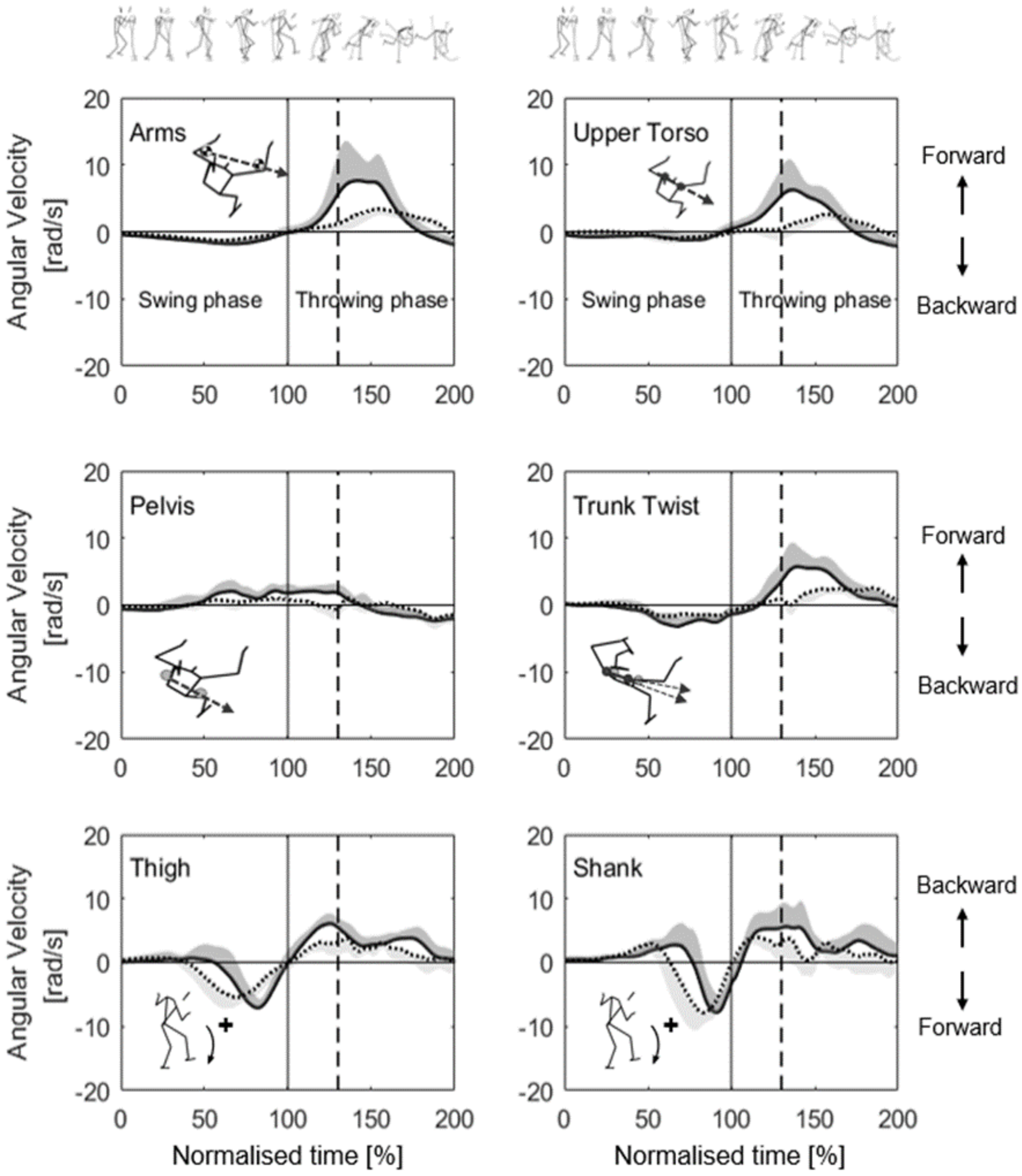

Figure 3-6. Mean (standard deviation) time-series data for the kinematics of the upper body and sweeping leg of the tori. Solid line: black belt group; dotted line: white belt group; vertical dashed line: instant of sweeping leg contact. The fill for the standard deviation of the positive direction represents the standard deviation of the values for the black belt group, and that for the negative direction represents the standard deviation of the values for the white belt group.

Table 3-1. Comparison of kinematic variables between black and white belt judokas.

Variable	Black belts	White belts	t-value	df	p-value	Cohen's d	95% CI
Positive peak angular momentum of the uke (kg·m^2/s)							
H_{trunk}	11.86 ± 2.50	5.36 ± 0.68	8.646	12.911	**< .001*****	3.554	4.87 to 8.12
H_{Leg}	30.93 ± 3.16	22.79 ± 6.73	3.515	12.281	**0.004****	1.548	3.11 to 13.16
Negative peak angular velocity of the tori (rad/s)							
ω_{Arms}	-1.98 ± 0.63	-1.47 ± 0.42	-2.258	19.253	**0.036***	-0.950	-0.98 to -0.04
$\omega_{Upper\ Torso}$	-1.73 ± 0.64	-1.38 ± 0.48	-1.460	19.823	0.160	-0.617	-0.85 to 0.15
$\omega_{Trunk\ Twist}$	-4.08 ± 0.97	-2.52 ± 0.62	-4.546	18.851	**< .001*****	-1.909	-2.28 to -0.84
ω_{Thigh}	-8.12 ± 1.46	-6.26 ± 0.70	-3.897	16.411	**0.001****	-1.621	-2.87 to -0.85
ω_{Shank}	-8.66 ± 2.82	-9.14 ± 1.30	0.528	16.061	0.605	0.219	-1.45 to 2.41
Positive peak angular velocity of the tori (rad/s)							
ω_{Arms}	12.17 ± 5.66	3.98 ± 1.04	4.916	11.890	**< .001*****	2.013	4.56 to 11.83
$\omega_{Upper\ Torso}$	8.04 ± 4.11	3.10 ± 0.72	4.095	11.798	**0.002****	1.677	2.31 to 7.58
$\omega_{Trunk\ Twist}$	7.78 ± 3.07	4.37 ± 1.05	3.608	13.936	**0.003****	1.488	1.39 to 5.45
ω_{Thigh}	6.54 ± 1.21	5.41 ± 1.29	2.104	18.835	**0.049***	0.903	0.01 to 2.25
ω_{Shank}	8.53 ± 3.06	6.67 ± 2.06	1.694	19.262	0.106	0.713	-0.44 to 4.16

Mean ± standard deviation.

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

Table 3-2. Comparison of temporal parameters between black and white belt judokas in normalised time (%).

Variable	Black belts	White belts	t-value	df	p-value	Cohen's d	95% CI
Negative peak angular velocity temporal parameters of the tori (% Normalised time)							
ω_{Arms}	68.00 ± 10.07	62.60 ± 9.88	1.265	19.422	0.221	0.541	-3.52 to 14.32
$\omega_{\text{Upper Torso}}$	69.00 ± 21.18	71.00 ± 11.89	-0.279	17.782	0.784	-0.116	-17.09 to 13.09
$\omega_{\text{Trunk Twist}}$	69.17 ± 14.30	67.80 ± 18.74	0.189	16.641	0.852	0.082	-13.90 to 16.63
ω_{Thigh}	80.33 ± 5.40	68.00 ± 7.21	4.465	16.438	**< .001*****	1.936	6.49 to 18.18
ω_{Shank}	90.00 ± 4.41	81.40 ± 5.68	3.906	16.838	**0.001****	1.691	3.95 to 13.25
Positive peak angular velocity temporal parameters of the tori (% Normalised time)							
ω_{Arms}	146.75 ± 8.80	156.90 ± 10.98	-2.359	17.188	**0.030***	-1.020	-19.22 to -1.08
$\omega_{\text{Upper Torso}}$	143.42 ± 9.33	160.80 ± 14.00	-3.355	15.190	**0.004****	-1.461	-28.42 to -6.35
$\omega_{\text{Trunk Twist}}$	148.42 ± 15.15	173.20 ± 18.91	-3.345	17.179	**0.004****	-1.446	-40.40 to -9.16
ω_{Thigh}	130.17 ± 13.58	134.70 ± 11.01	-0.865	19.993	0.397	-0.367	-15.47 to 6.40
ω_{Shank}	135.00 ± 10.17	134.50 ± 13.06	0.099	16.873	0.923	0.043	-10.20 to 11.20
Time difference of upper body part relative to shank of the tori (% Normalised time)							
$\omega_{\text{Arms} \rightarrow \text{shank}}$	-11.75 ± 15.05	-22.40 ± 11.06	1.910	19.743	0.071	0.807	-0.99 to 22.29
$\omega_{\text{Upper Torso} \rightarrow \text{shank}}$	-8.42 ± 15.29	-26.30 ± 11.01	3.181	19.646	**0.005****	1.342	6.14 to 29.62
$\omega_{\text{Trunk Twist} \rightarrow \text{shank}}$	-13.42 ± 19.41	-38.70 ± 25.32	2.588	16.697	**0.019***	1.121	4.64 to 45.93

Mean ± standard deviation.

$\omega_{\text{Arms} \rightarrow \text{shank}}$, $\omega_{\text{Upper Torso} \rightarrow \text{shank}}$, $\omega_{\text{Trunk Twist} \rightarrow \text{shank}}$: normalised time difference in the positive peak angular velocities of the arms, upper torso, and trunk twist relative to those of the shank during the throwing phase.

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

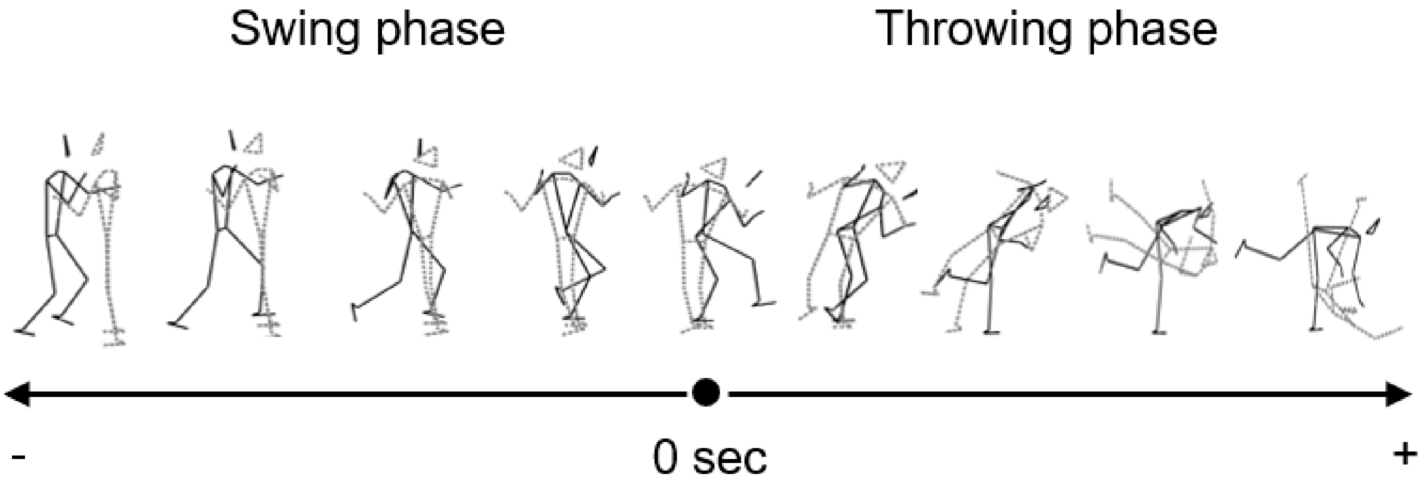

Figure 3-7. Phases of osoto-gari in raw time (seconds).

For this calculation, the time at which the sweeping leg toe marker was at the highest position on the vertical axis was defined as 0 s. The swing phase is defined as negative time. The throwing phase is defined as positive time.

Table 3-3. Comparison of temporal parameters between black and white belt judokas based on raw time (seconds).

Variable	Black belts	White belts	t-value	df	p-value	Cohen's d	95% CI
Negative peak angular velocity temporal parameters of the tori (raw time [s])							
ω_{Arms}	-0.22 ± 0.04	-0.26 ± 0.08	1.372	13.155	0.193	0.602	-0.02 to 0.10
$\omega_{\text{Upper Torso}}$	-0.21 ± 0.16	-0.20 ± 0.08	-0.299	16.831	0.768	-0.125	-0.13 to 0.09
$\omega_{\text{Trunk Twist}}$	-0.21 ± 0.10	-0.20 ± 0.14	-0.242	15.47	0.812	-0.106	-0.126 to 0.10
ω_{Thigh}	-0.14 ± 0.04	-0.22 ± 0.05	3.821	15.755	**0.002****	1.661	0.034 to 0.12
ω_{Shank}	-0.07 ± 0.03	-0.13 ± 0.05	3.437	14.626	**0.004****	1.5	0.021 to 0.09
Positive peak angular velocity temporal parameters of the tori (raw time [s])							
ω_{Arms}	0.27 ± 0.07	0.41 ± 0.14	-3.074	12.568	**0.009****	-1.352	-0.247 to -0.04
$\omega_{\text{Upper Torso}}$	0.25 ± 0.07	0.44 ± 0.15	-3.597	12.509	**0.003****	-1.583	-0.305 to -0.08
$\omega_{\text{Trunk Twist}}$	0.28 ± 0.10	0.51 ± 0.14	-4.625	15.801	**< .001*****	-2.01	-0.347 to -0.13
ω_{Thigh}	0.14 ± 0.05	0.19 ± 0.08	-1.631	14.126	0.125	-0.713	-0.111 to 0.02
ω_{Shank}	0.19 ± 0.06	0.22 ± 0.09	-0.756	15.295	0.461	-0.329	-0.095 to 0.05
Time difference of upper body part relative to shank of the tori (raw time [s])							
$\omega_{\text{Arms} \rightarrow \text{shank}}$	-0.08 ± 0.09	-0.20 ± 0.09	3.181	19.321	**0.005****	1.362	0.04 to 0.20
$\omega_{\text{Upper Torso} \rightarrow \text{shank}}$	-0.06 ± 0.09	-0.22 ± 0.10	4.012	17.829	**< .001*****	1.73	0.08 to 0.25
$\omega_{\text{Trunk Twist} \rightarrow \text{shank}}$	-0.08 ± 0.11	-0.30 ± 0.15	3.731	16.372	**0.002****	1.618	0.09 to 0.33

Mean ± standard deviation.

$\omega_{\text{Arms} \rightarrow \text{shank}}$, $\omega_{\text{Upper Torso} \rightarrow \text{shank}}$, $\omega_{\text{Trunk Twist} \rightarrow \text{shank}}$: time difference in the positive peak angular velocities of the arms, upper torso, and trunk twist relative to those of the shank during the throwing phase.

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

3.4. DISCUSSION

This study clarifies the biomechanical factors that result in effective execution of the osoto-gari technique by comparing the parameters of athletes of different skill levels (i.e., black belt and white belt judokas). First, our findings showed that the peak angular momentums of the trunk and leg of the black belt group were significantly greater than those of the white belt group (Table 3-1), which supports our first hypothesis. These results suggested that the black belt judokas were able to create two large angular momentum states through upper body pushing and leg reaping to effectively rotate the uke's body.

When the tori's lead foot left the ground, the arms, upper torso, and trunk gradually rotated backward in both groups (Figure 3-6). Significant differences were found in the peak negative angular velocities of the arms and trunk (Table 3-1). Imamura et al. (2006) indicated that when the tori pulled the uke, uke would create a slight resistance to the tori's pulling. Tori could use the uke's resistance so that it fits into the throw easily. This strategy is consistent with the basic philosophy of judo, which stresses using the opponent's strength to one's advantage. The peak angular velocities of the arms and trunk were larger in the black belt group than in the white belt group, which could indicate that the black belt judokas pull the uke’s upper body more strongly by twisting the trunk to force the uke to exert some resistance. Additionally, the black belt judokas rotated the upper body backward strongly, which might be a preparatory action to effectively pushing the opponent's upper body backward. This is because osoto-gari is mainly used to throw the opponent backward, but the upper body rotates opposite to the throwing direction as a countermovement before throwing, which may effectively create pushing momentum that increases the effectiveness of the throw. However, we do not recommend that the tori pull excessively because it is easy to knock oneself out of balance. From the beginning of the throwing phase, the angular velocities of the upper body in both groups turned rapidly in the forward direction (Figure 3-6). The statistical results revealed that the peak positive angular velocities of the arms, upper torso and trunk were significantly larger in the black belt group (Table 3-1). Thus, the second hypothesis of this study was supported. These findings suggested that the black belt judokas generated a greater pushing momentum at the uke's upper body during the throw than the white belt judokas.

Notably, the timing of the peak angular velocities might reflect the superior whole-body coordination of the black belt judokas (Table 3-2). During the swing phase, we found a statistically significant difference in the normalised time of the appearances of the peak negative angular velocities of the thigh and shank between groups. This suggests that black belt judokas might intentionally delay the swing of the sweeping leg when the pivot leg steps on the floor instead of swing up immediately, similar to the white belt judokas. We considered that delaying the sweeping leg may store strength or energy for building a kinetic chain to perform an effective reaping action.

During the throwing phase, the time of the peak angular velocity of the shank was at approximately 135% of the normalised time and was the same for both black and white belt judokas, suggesting that the two groups performed similar reaping actions. The peak shank angular velocity was preceded by the peak thigh angular velocity in the black belt judokas (130.17% normalised time), whereas there was no such difference in timing between the thigh and shank (134.70% and 134.50%) in the white belt judokas. These results are in agreement with Imamura and Johnson (2003), who found that in white belt judokas, the leg was swept as a rigid segment, not as a kinetic chain.

In contrast, the timing of the peak angular velocities of the arms, upper torso, and trunk of the black belt judokas was earlier than that of the white belt judokas, and the time difference in the peak angular velocities of the upper torso and trunk relative to that of the shank was smaller than that of the white belt judokas. These results supported our third hypothesis: upper body pushing was performed almost simultaneously with the reaping action in the black belt judokas, whereas in the white belt judokas, they were performed separately. The white belt judokas were focused on leg reaping and not on whole-body coordination (Lage et al., 2014). In addition, the time of the trunk twist in the white belt judokas was at 173% normalised time, which was delayed considerably compared to the black belt judokas. It is suggested that the white belt judokas were not able to take advantage of the trunk twist motion for upper body pushing. These differences in body coordination might explain the differences in osoto-gari skill, and the larger observed momentum of the uke with a black belt tori could also reduce the action time of the throwing phase considerably (Figure 3-4). It should be noted that not only body coordination skills but also muscle strength and/or trunk flexibility contributed to the effective throws of the black belt judokas.

Some judo specialists (Yamashita, 1992; Kano, 1994; Daigo, 2005; Imamura and Jonhson, 2003) have emphasized that upper body pushing must be performed at the time of sweeping leg contact. In judo matches, executing leg reaping and upper body pushing separately results in a failed throw or even the risk of a counterattack by the opponent, suggesting that synchronization of upper body contact and the sweeping action may be an important factor in successfully executing osoto-gari from a judo coaching perspective. Therefore, we recommend that coaches pay more attention to the coordination and linkage of the two actions during the throwing phase.

In the present study, we used normalised data to analyse the differences in the timing of the appearance of the peak angular velocity between the two groups. However, the normalised times may not truly reflect the temporal differences. To investigate this issue, we re-ran the analyses using the original data. Table 3-3 shows the results for the raw time data (same as Table 3-2). During the swing phase, the timing of the peak negative angular velocities of the thigh and shank in the black belt group were -0.14 ± 0.04 and -0.07 ± 0.03 s, respectively, which were significantly later than those in the white belt group (-0.22 ± 0.05 and -0.13 ± 0.05 s). During the throwing phase, the timing of the peak positive angular velocities of the arm, upper torso, and trunk in the black belt group were 0.27 ± 0.07, 0.25 ± 0.07, and 0.28 ± 0.10 s, respectively, which were significantly earlier than those in the white belt group (0.41 ± 0.14, 0.44 ± 0.15, and 0.51 ± 0.14 s, respectively). Finally, the differences in the timing of the peak angular velocities of the upper torso and trunk relative to that of the shank in the black belt group were -0.08 ± 0.09, -0.06 ± 0.09, and -0.08 ± 0.11 s, respectively, which were significantly smaller than those of the white belt group (-0.20 ± 0.09, -0.22 ± 0.10, and -0.30 ± 0.15 s, respectively). These results are in agreement with the previous finding using the normalised data that upper body pushing was performed almost simultaneously with the reaping action by the black belt judokas, whereas the white belt judokas had a time lapse of approximately 0.2 s between the two actions. This may be the main reason why the motion time of the throwing phase in the white belt group was longer than that in the black belt group. Overall, the use of normalised data to analyse the temporal differences between the two groups did not impact the results or interpretation of the data.

3.5. CONCLUSION

In summary, black belt judokas can create a large angular momentum in the uke's upper body and leg. The findings showed that the black belt judokas could generate greater pushing momentum by twisting the trunk to obtain a strong upper body to upper body contact during the throwing phase. The black belt judokas executed the sweeping of the leg as a sequential kinetic chain, whereas the white belt judokas maintained the leg as a rigid segment during leg sweeping. The black belt judokas delayed the swinging up of the sweeping leg during the swing phase to better build the kinetic chain while in contact with the opponent's leg. In the mid-term throwing phase, the peak angular velocities of the upper body part in the black belt appeared near sweep contact compared to the white belt. Synchronized upper body contact and leg reaping might be crucial biomechanical factors for rendering a powerful throw in osoto-gari. Coaches should pay more attention to the coordination and linkage of the two actions.

CHAPTER 4

In Chapter 3, the linkage between the tori's sweeping leg and upper body was clarified from a kinematic perspective, revealing how to effectively rotate the uke’s body. However, the kinematics and kinetics of the support leg have not been explored. To deepen the understanding of the mechanism of osoto-gari, a kinetic study on the supporting leg in osoto-gari should be conducted. Especially like the osoto-gari, such a single leg throwing action, the supporting leg provides force or energy to the upper body and sweeping leg and supports the weight of the tori and uke during the throw. We considered that proper exertion of the supporting leg muscles may play a crucial role in the effectiveness of the throw.

4.1. INTRODUCTION

Osoto-gari is one of the most popular throwing techniques in modern judo, being frequently used in judo matches and positioned as the first of the five domains of judo throwing techniques (Kano, 1994; Matsumoto, 1975). In other words, this technique is relatively easy to master, so it is considered to be very appropriate for beginners (Matsumoto, 1975; Imamura et al., 2006; Almansba et al., 2008). In osoto-gari, leg sweeping is an important technique: it is required that the thrower raise the sweeping leg upward drastically (Figure 4-1(3-4)) to gain potential energy and then strongly sweep it backward, making contact with the opponent's outer leg (Figure 4-1(5)) (Daigo, 2005; Kano, 1994; Yamashita, 1992). Thus, a powerful leg sweep can cause the opponent's feet to leave the ground in an instant, and then the thrower can easily push the opponent’s upper body backward to the ground.

The question of how to effectively execute the leg sweeping action in osoto-gari has attracted the attention of judo experts. Imamura and Johnson (2003) investigated biomechanical differences in osoto-gari by comparing novice and black belt judokas. They reported that the peak ankle plantar flexion velocity of the sweeping leg of black belt judokas was significantly greater than that of novices during sweep contact. Additionally, Liu et al. (2021) found that the timing of the upwards swinging of the sweeping leg occurred significantly later in the black belt judokas than in the white belt judokas before sweep contact. Kuo (2001) compared two styles of leg sweeps in osoto-gari throwing, the knee-flexed style and the traditional knee-extended style and found that the former style produces a greater sweeping force than the latter. These studies obtained results and insights that can help improve the performance of sweeping actions to some extent. However, they focused on the sweeping leg, and less attention has been given to the function of the supporting leg during sweep performance.

In an osoto-gari action, sweeping of the leg is a multijoint link motion involving the thigh, shank, and foot; the execution of the action follows the kinetic chain principle

(Imamura and Johnson, 2003), with a great momentum being generated by the supporting leg via the trunk and then transmitted to the sweeping leg to generate the greatest possible distal segment speed when reaping the opponent's leg. Therefore, based on the kinetic chain principle, the external force acting at the end of the supporting leg is a prerequisite for a high sweep leg velocity at sweep impact. A biomechanical study of harai-goshi (i.e., a leg throwing technique similar to osoto-gari) found a significant correlation between the anteroposterior GRF of the supporting leg and the horizontal velocity of the sweeping leg during the throw (Pucsok et al. 2001). However, no studies have investigated the kinetics of the lower limbs in osoto-gari.

The following is a brief description of the biomechanical analysis of osoto-gari performed in this study. The osoto-gari technique involves rotational motion during a throw (sagittal plane). As shown in Figure 4-2, with resistance from the uke ignored, the thrower can voluntarily manipulate the GRFs with two supporting legs: the sweeping leg (a) and the pivot leg (b). Due to the CoM and centre of pressure (CoP) positional excursion during the throw, the external forces acting on the two support legs generate a moment around the thrower's CoM. In fact, measuring and analysing the external moment of an individual's CoM has been used to study explosive hitting techniques. Ae et al. (2017) analysed baseball batting technique by measuring external moments. Han et al. (2019) investigated the relationship between the external moments generated by both legs and the club head velocity in golf. They pointed out that generation of the external moment about the CoM could promote rotation of the proximal segment and drive the distal segments together, ultimately accelerating the bat or club head speed. However, the function of the external moment in the sweeping action of osoto-gari has not been investigated.

Osoto-gari is a technique performed during one-leg standing (see Figure 4-2(b)). We considered that during execution of the leg sweeping action, muscle exertion at the three joints of the lower limb closest to the ground plays an important role in controlling the shift of the CoM and the generation of GRFs. For this reason, analysing the dynamics (joint moment, joint power) of the lower limbs of the tori may help explain the magnitude and direction of the generated GRF and could provide more comprehensive information on osoto-gari, especially on the generation of the swing velocity of the sweeping leg.

The purpose of the present study was to determine the kinetic characteristics of osoto-gari and to investigate the relationship between kinetic variables and the sweeping leg velocity at sweep contact. We proposed two hypotheses: (1) the peak external moment generated by the force of the pivot leg is significantly correlated with the sweeping leg velocity at sweep contact; and (2) the peak joint moment and joint power of the pivot leg are related to the sweeping leg velocity at sweep contact.

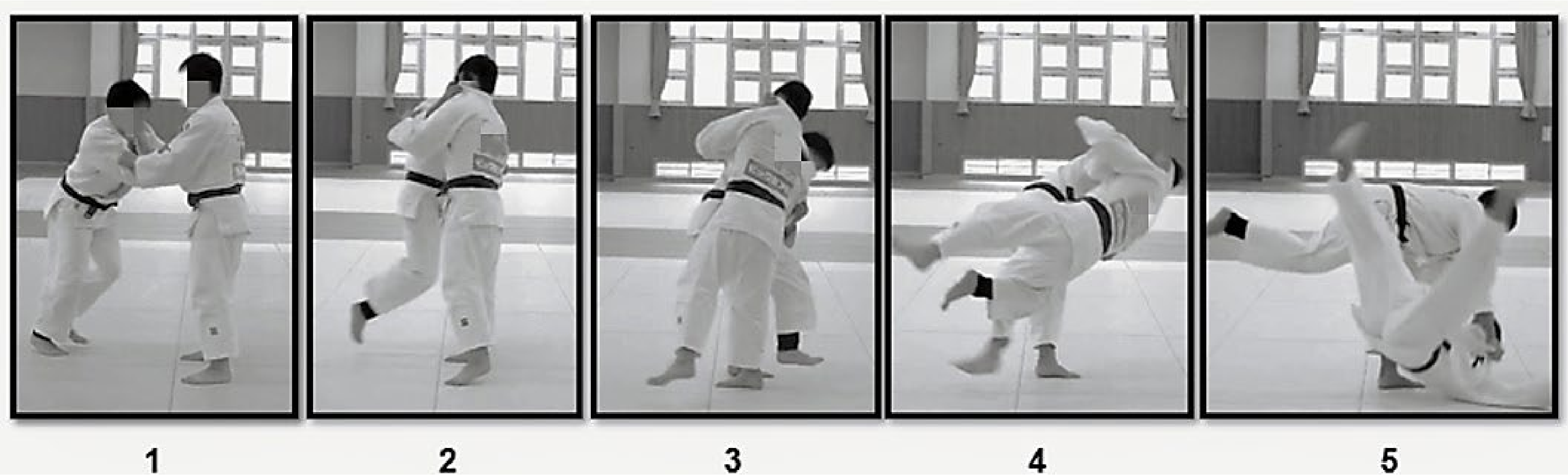

Figure 4-1. Sequence of photographs of the leg sweeping action in osoto-gari. The tori (thrower; the one on the left)) and uke (faller; the one on the right) are shown. In this study, the left leg of the tori is defined as the pivot leg, and the right leg is defined as the sweeping leg. The pivot leg takes one large step forward (1-2), the sweeping leg swings upwards and forward (3), then the sweeping leg sweep makes contact with the uke’s right leg and push his/her upper body to the ground(4-5).

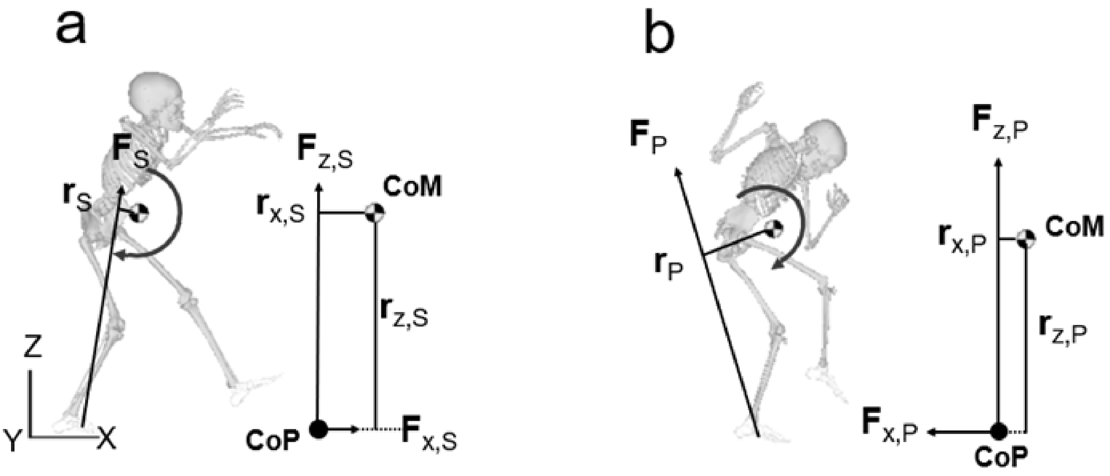

Figure 4-2. Model of the osoto-gari technique in the sagittal plane.

(a) shows the interaction between the sweeping leg and the ground (located in Figure 4-1(2)). (b) shows the interaction between the pivot leg and the ground (located in Figure 4-1(5)). F_S and F_P refer to the GRF acting on the sweeping leg and pivot leg, respectively. The external moment arm (r) is defined by the distance from the CoM to the CoP of each leg. The external moment about the CoM of the tori's body is due to the GRF acting on each leg.

4.2. METHODS

4.2.1. Participants

Fifteen male black belt judokas (age: 20.7 ± 2.5 years, height: 173.3 ± 4.4 cm, mass: 84.4 ± 13.2 kg) served as toris (throwers) and participated in this study. The black belt judokas participated in the university's judo team and had at least seven years of judo experience. In addition, a black belt male judoka (age: 22 years, height: 173 cm, mass: 81 kg) who had nine years of judo experience served as the uke (faller) in this study. The study's purpose and risks were explained to the participants prior to enrolment, and all participants provided written, informed consent before participating in this study.

4.2.2. Data collection

The experiment was performed in an indoor biomechanics laboratory. The participants (the tori and uke) wore black sports tights, and 47 reflective markers were placed on their bodies. The location of the reflective markers was the same as that in Chapter 3. The uke was instructed to wear specially designed judo gear, stand on one of the force plates and provide no conscious resistance. The tori was instructed that the sweeping leg and the pivot leg must contact separate force plates. Prior to the actual measurements, the participants were allowed to practice osoto-gari to familiarize themselves with the measurement environment. The tori was instructed to perform osoto-gari throwing with maximal effort. For every throw they completed, the tori was asked to evaluate his throwing performance on a scale of 1 to 5 (1 = poor, 2 = below average, 3 = average, 4 = good, 5 = excellent), as in Ishii et al. (2018). They were asked to repeat the throws until two trials rated as 4 or 5 were successfully captured. Three advanced judo coaches from the university (coaching experience: 23, 40, and 30 years) then independently evaluated the two trials and selected the trial with the best performance, which was used for subsequent motion analysis.

The motion of the reflective markers was recorded using a 14-camera Mac3D motion analysis system (Motion Analysis Corp., Santa Rosa, CA, USA) with a sampling rate of 250 Hz. GRFs were recorded using four force plates (BMS600900-4K, Advanced Mechanical Technology Inc., Watertown, MA, USA) at 1000 Hz. For the global coordinate system shown in Figure 4-2 (a), the X-axis is defined as the anterior/posterior direction from the tori to the uke, the Y-axis is defined as the medial/lateral direction, and the Z-axis is defined as the vertical direction.

4.2.3. Data analysis

All data analysis was performed using MATLAB 2016a (MathWorks Inc., Natick, MA, USA). Three-dimensional marker trajectory data were smoothed using a 4th-order low-pass Butterworth filter with a cut-off frequency of 12 Hz, and the GRF data were smoothed using the same method with a cut-off frequency of 50 Hz. Then, the GRF data were downsampled to 250 Hz so that they could be synchronized with the marker data.

The body of the tori was modelled as 15 rigid link segments, including the head, left/right arms, left/right forearms, left/right hands, left/right feet, left/right shanks, left/right thighs, upper trunk, and lower trunk. In this model, the trunk was divided into the upper and lower trunk. The position of the CoM of the whole body and the inertial parameters of each segment were estimated using the anthropometric data for Japanese athletes reported by Ae et al. (1992). The velocity of the whole-body CoM was calculated through numerical differentiation using the CoM position. In addition, the ankle, knee, and hip joint centres were calculated using the same method as in a previous study (Koshida et al., 2016).

The osoto-gari motion was divided into the swing and throwing phases, as in CHAPTER 3.

4.2.4. Calculated parameters

1) Velocity of the sweeping leg of the tori

To calculate the velocity of the sweeping leg, Pucsok et al. (2001) pointed out that the horizontal velocity of the sweeping leg was a key indicator of the effectiveness of the sweeping leg action in judo. Therefore, we selected the ankle joint centre as a representative point (as shown in Figure 4-3) and calculated its horizontal velocity (along the X-axis) through numerical differentiation.

2) External moment around the whole-body CoM of the tori

The external moment M due to the GRF was calculated with the following equation:

$$\mathrm{M} = \mathrm{r}_{CoM\rightarrow iCoP}\times \mathrm{F}_{iGRF}$$

where $\mathrm{r}_{CoM\rightarrow iCoP}$ is the external moment arm vector formed by individual CoPs relative to the tori's CoM. F_{iGRF} is the external force vector acting on the individual leg. The $\mathrm{r}_{CoM\rightarrow iCoP}\times \mathrm{F}_{iGRF}$ term represents the external moment M generated about the whole-body CoM of the tori by the individual GRFs. The force and moment arm data were normalised to the thrower's body mass (kg) and body height (m), respectively. The external moment was normalised by the body mass (kg) and body height (m) of the tori and expressed in N/kg.

3) Joint force and joint moment of the lower limb of the tori

The ankle, knee, and hip joint moments of the lower limbs were calculated using the bottom-up inverse dynamics method with the Newton-Euler equation (Winter, 2009). The joint force JF_i was calculated with the following equation:

$$JF_i = m_i a_i + JF_{i-1} + m_i g$$

where JF_{i-1} is the joint force applied to segment i by the distal segments adjacent to i. m_i is the mass of segment i. a_i and g are the linear acceleration and gravitational acceleration of the CoM of segment i, respectively. The joint moment JM_i was calculated with the following equation:

$$JM_i = I_i \dot{\omega}_i + \omega_i \times I_i \omega_i - (r_i \times JF_i - r_{i-1} \times JF_{i-1} - JM_{i-1})$$

where the $I_i \dot{\omega}_i + \omega_i \times I_i \omega_i$ term represents the sum of the moments of segment i, I_i is the inertia matrix for segment i, $\dot{\omega}_i$ is the angular acceleration of segment i, ω_i is the angular velocity of segment i, and the $r_i \times JF_i$ and $r_{i-1} \times JF_{i-1}$ terms are the moments applied to segment i by the adjacent proximal and distal segments, respectively. JM_{i-1} is the joint moment applied to segment i by the adjacent distal segment. The calculated joint moments were transformed into the joint coordinate systems (JCSs). The JCSs of the ankle, knee and hip were defined using the same method as in the study of Ae et al.

(2017). The joint moment was normalised by the body mass (kg) of the tori and expressed in Nm/kg.

4) *Joint power of the lower limb of the tori*

$$JP_i = JM_i \; J\omega_i$$

Joint power JP_i was calculated as the product of each joint moment (JM_i) and its corresponding joint angular velocity ($J\omega_i$). The joint power was normalised by the tori's body mass (kg) and expressed in W/kg.

In this paper, we focused on the sagittal plane, and the parameters calculated included the following: GRF: anterior (+)/posterior (-) component and upward (+) component, moment arm: anterior (+)/posterior (-) component and downward (-) component, external moment: clockwise (+)/counterclockwise (-), joint motion of the lower limbs: ankle: dorsiflexion (+)/plantarflexion (-), knee and hip: flexion (+)/extension (-).

4.2.5. Statistical analysis

All statistical analyses were performed using JASP 0.14.1 (https://jasp-stats.org/). Pearson product-moment correlation coefficients were calculated for the peak sweeping leg velocity and the peak GRFs, peak external moments, peak joint moments, and peak joint powers. The level of significance was set at a p value < 0.05.

4.3. RESULTS

The peak sweeping leg velocity was -4.19 ± 0.99 m/s. The time of the appearance of the peak value was 128.93 ± 6.00% normalised time (Figure 4-3).

The GRFs acting on the sweeping leg gradually increased in the anterior direction (+) (Figure 4-4(a)) and upward direction (+) (Figure 4-4(b)) from the beginning of the swing phase. Both variables peaked at approximately 50% normalised time. The peak anterior force ($r = -0.535$, $p = 0.040$) and the peak upward force ($r = -0.579$, $p = 0.024$) were negatively correlated with the sweeping leg velocity at sweep contact (Table 4-1).

The ankle joint of the sweeping leg had a larger plantar flexion moment (-) in the mid-swing phase, and the peak value appeared at 50% normalised time (Figure 4-5(d)). The sweeping leg hip joint constantly generated an extension moment (-) with a peak value, but a slight flexion moment was observed after the mid-late swing phase (Figure 4-5(f)). The peak ankle plantar flexion moment was positively correlated with the sweeping leg velocity at sweep contact ($r = 0.548$, $p = 0.034$), whereas the peak hip extension moment was not (Table 4-1). The sweeping leg ankle plantar flexors exerted substantial positive power from 40% normalised time until the sweeping leg was off the ground (approximately 70% normalised time) (Figure 4-5(g)). The peak power of the sweeping leg ankle plantar flexor was negatively correlated with the sweeping leg velocity at sweep contact ($r = -0.788$, $p < 0.001$) (Table 4-1).

From the time the pivot leg touched the ground (approximately 50% normalised time), the forces acting on the pivot leg gradually increased in the posterior direction (-) and peaked at approximately 130% normalised time (Figure 4-6(a)). However, the peak value was not significantly correlated with the sweeping leg velocity (Table 4-2). The upward force increased steeply and exhibited two peak values (Figure 4-6(b)). The action of these forces on the pivot leg generated a large clockwise moment (+) about the tori's CoM from the late swing phase and reached a peak value almost simultaneously with sweep contact (Figure 4-6(e)). The peak clockwise moment ($r = -0.604$, $p = 0.017$) was negatively correlated with the sweeping leg velocity (Table 4-2).

A larger extension moment (-) was generated about the pivot leg knee joint from 50% to 170% normalised time, peaking at approximately 120% normalised time (Figure 4-7(e)). A larger flexion moment (+) was generated about the pivot leg hip joint from 70% to 170% normalised time, peaking at approximately 100% normalised time (Figure 4-7(f)). Both peak moments were correlated with the sweeping leg velocity at sweep contact (knee extensor: $r = 0.602$, $p = 0.018$; hip flexor: $r = -0.589$, $p = 0.021$) (Table 4-2). The pivot leg knee extensors exerted a small magnitude of negative power in the late swing phase and greater positive power in the throwing phase (Figure 4-7(h)). The pivot leg hip flexors exerted larger positive power from the late swing phase (Figure 4-7(i)).

The peak positive power of the pivot leg knee extensor was negatively correlated with the sweeping leg velocity at sweep contact (r = -0.745, p = 0.001), whereas the peak positive power of the pivot leg flexor was not (Table 4-2).

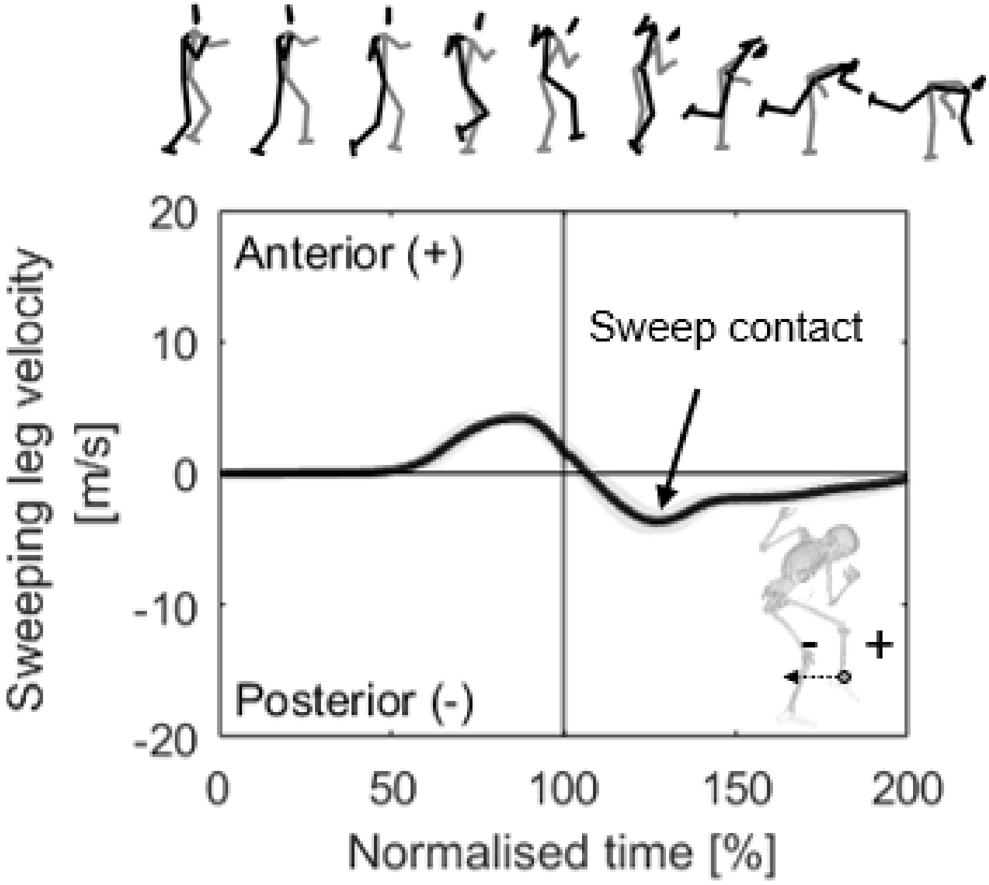

Figure 4-3. The velocity of the sweeping leg. The black arrow represents the peak negative velocity of the ankle joint marker on the sweeping leg in the posterior (-) direction. In this study, this value is defined as the peak leg sweeping velocity at sweep contact.

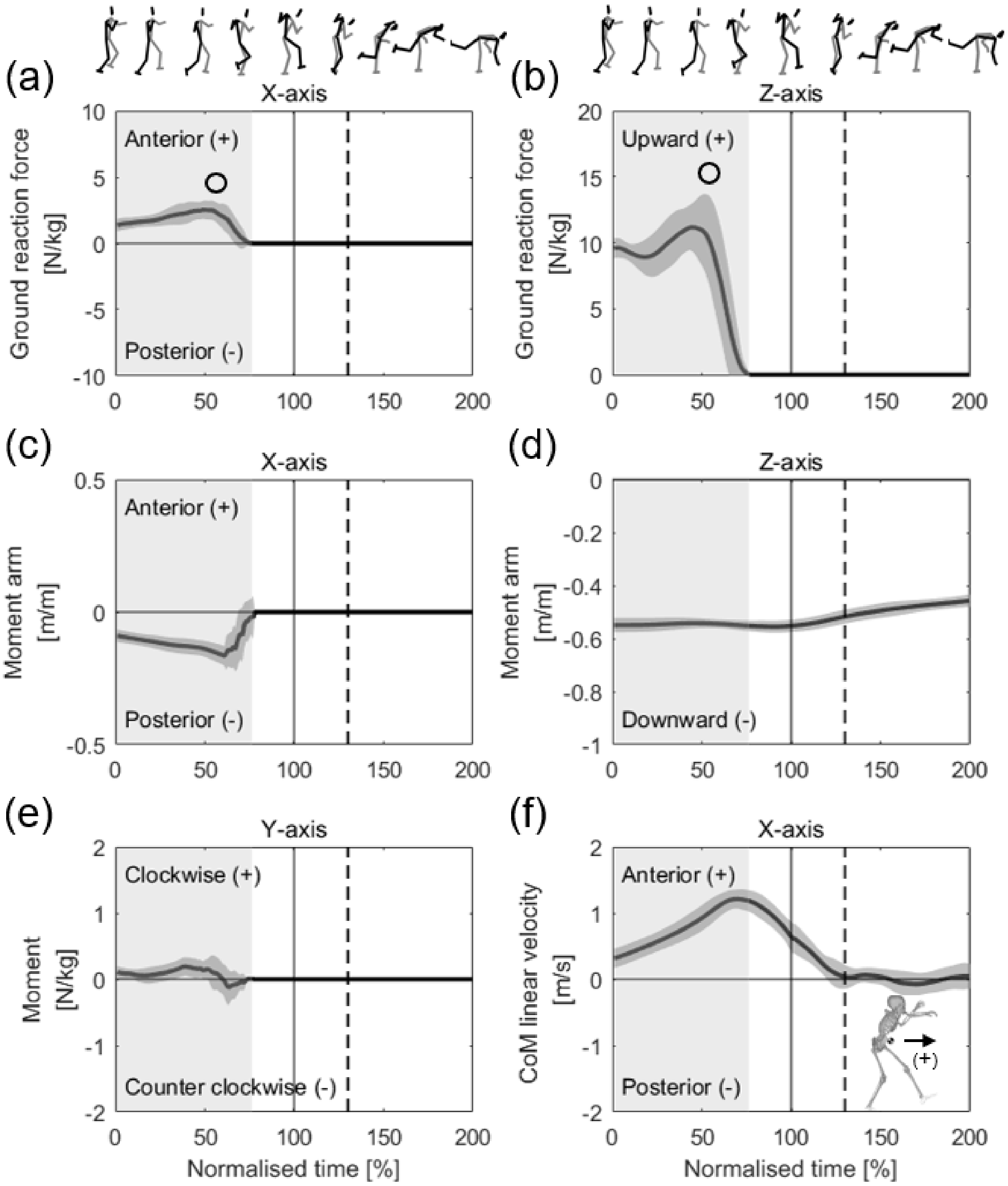

Figure 4-4. Mean (standard deviation) time-series data for the force (top), moment arm (middle) and moment (bottom, left) for the sweeping leg and the linear velocity of the tori's CoM (bottom, right). The area in grey represents the time period (0%-75% normalised time) that the sweeping leg contact with the ground. Vertical dashed line (black): the instant of sweep contact. Peak values are marked by a black circle (○) and were used in the correlation analysis.

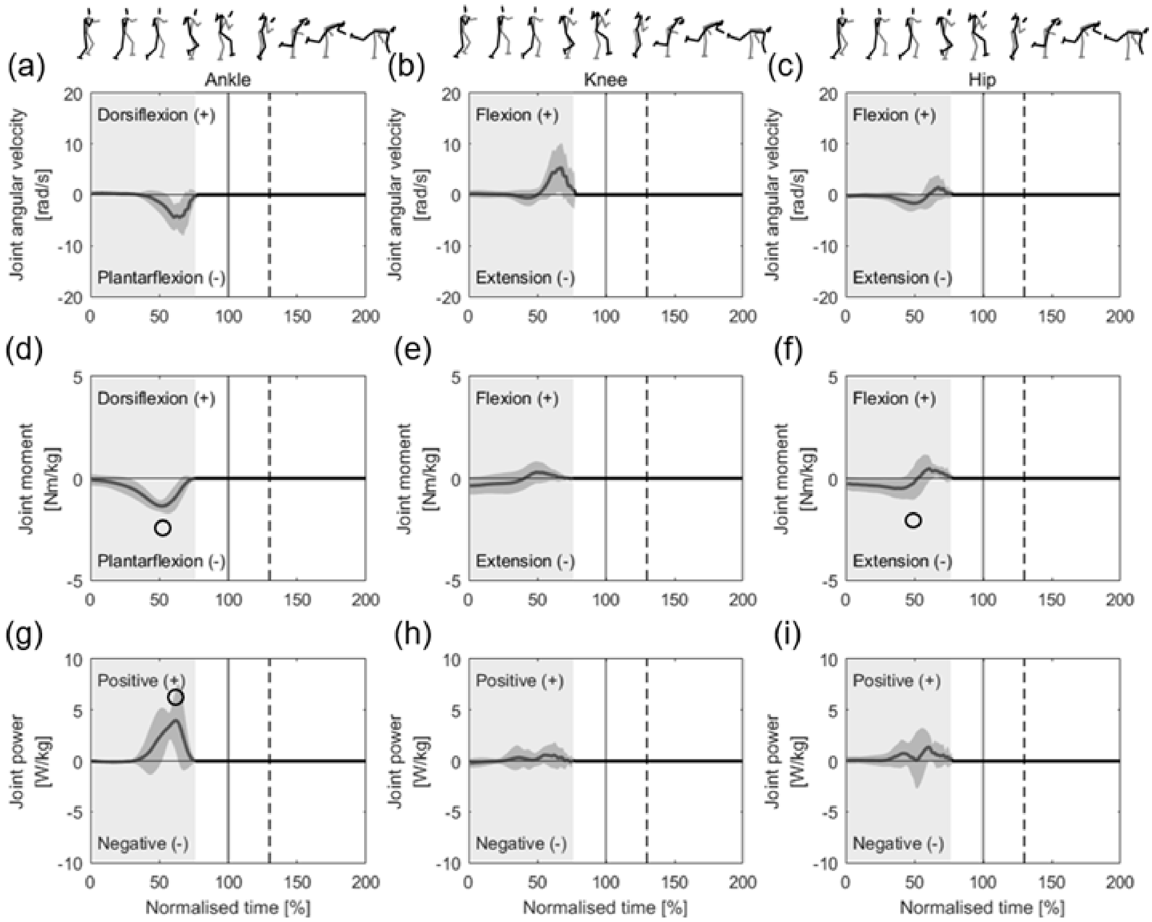

Figure 4-5. Mean (standard deviation) time-series data for the joint angular velocity (top), joint moment (middle), and joint power (bottom) of the sweeping leg. The area in grey represents the time period (0%-75% normalised time) that the sweeping leg contact with the ground. Vertical dashed line (black): the instant of sweep contact. Peak values are marked by a black circle (○) and were used in the correlation analysis.

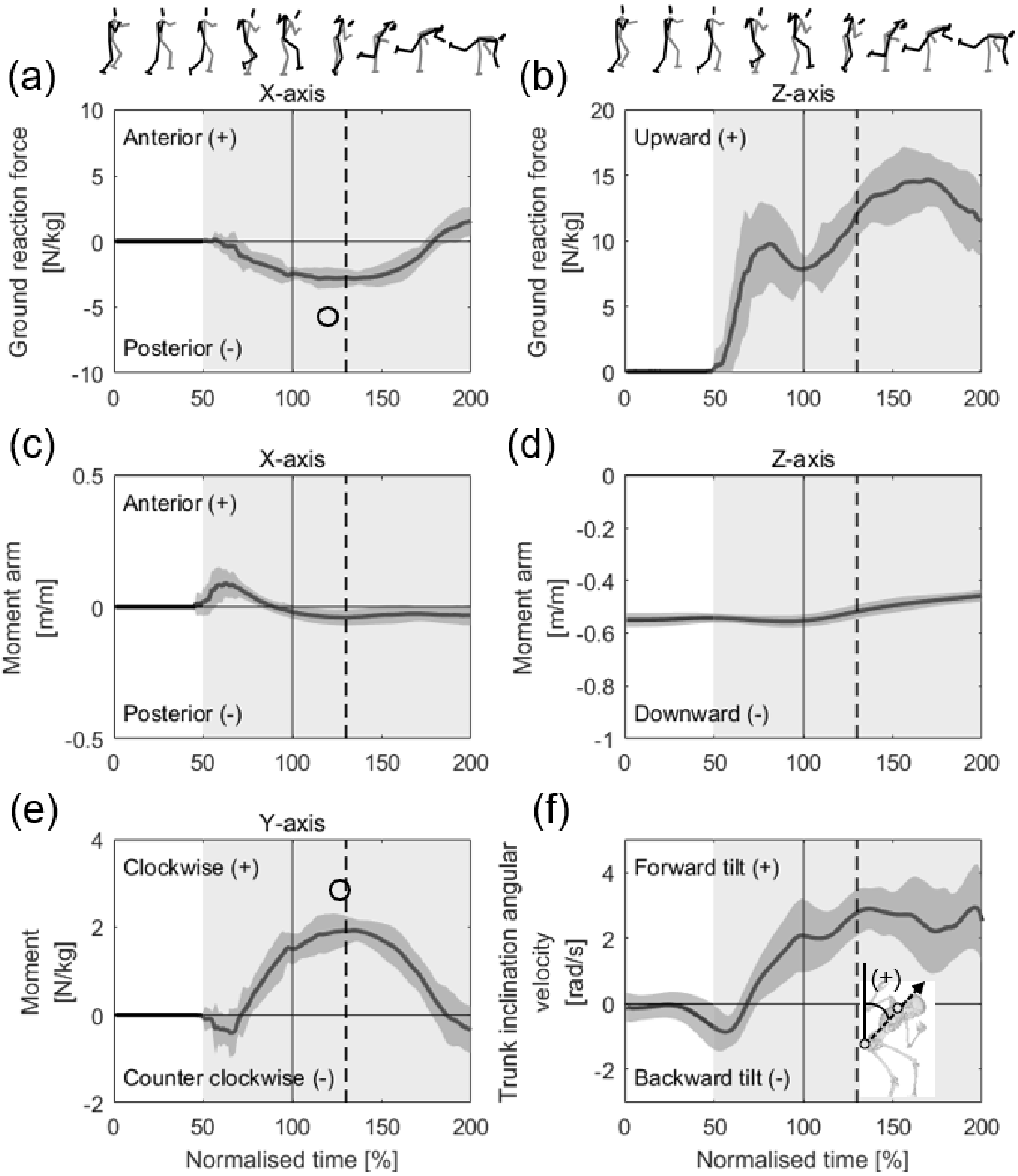

Figure 4-6. Mean (standard deviation) time-series data for the force (top), moment arm (middle) and moment (bottom, left) for the pivot leg and trunk inclination angular velocity (bottom, right). The area in grey represents the time period (50%-200% normalised time) that the pivot leg contact with the ground. Vertical dashed line (black): the instant of sweep contact. Peak values are marked by a black circle (○) and were used in the correlation analysis.

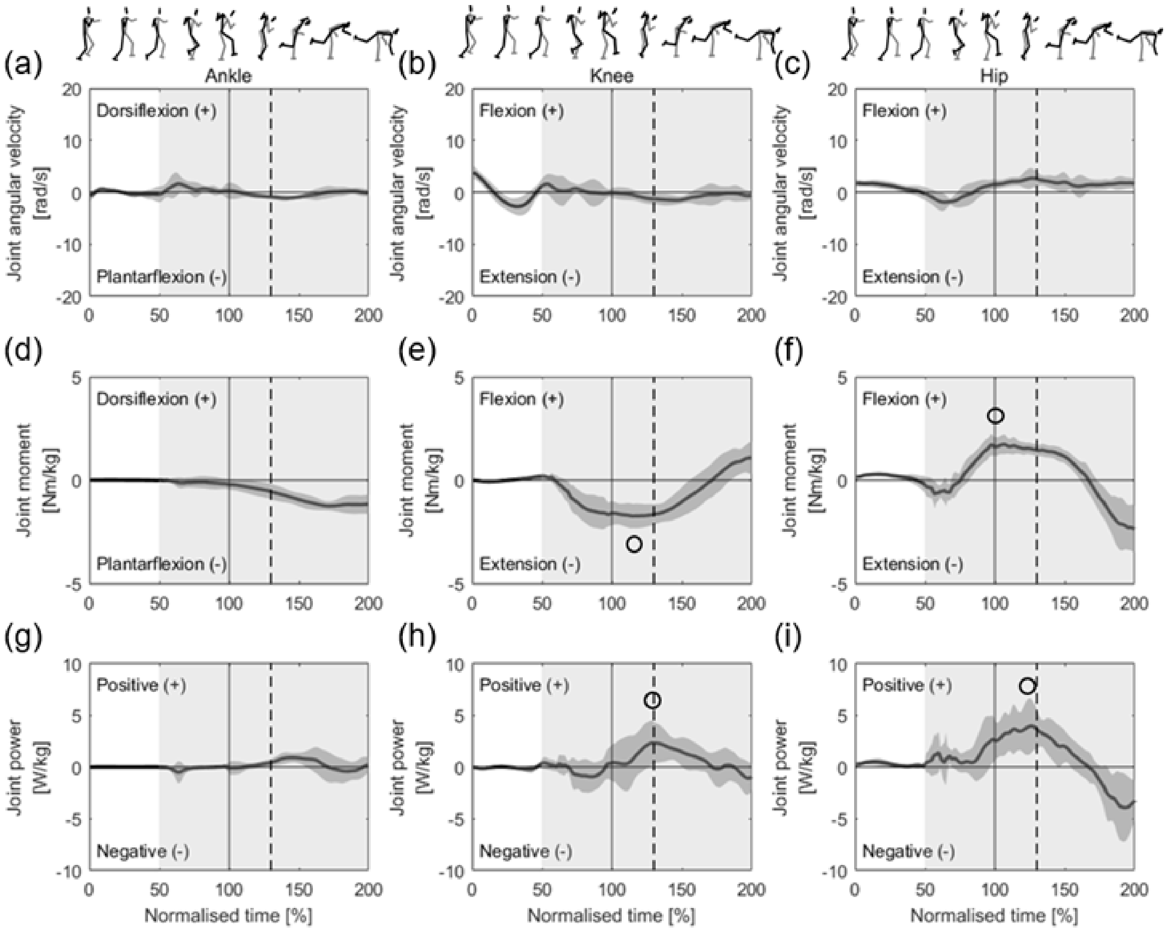

Figure 4-7. Mean (standard deviation) time-series data for the joint angular velocity (top), joint moment (middle), and joint power (bottom) of the pivot leg. The area in grey represents the time period (50%-200% normalised time) that the pivot leg contact with the ground. Vertical dashed line (black): the instant of sweep contact. Peak values marked by a black circle (○) and were used in the correlation analysis.

Table 4-1 . Peak kinetic variables for the sweeping leg and their correlation with the sweeping leg velocity at sweep contact

Variable	**Mean ± s**	**r**	**p**	**95% CI**
Ground reaction force (N/kg)				
Anterior (+) GRF	3.02 ± 0.59	**-0.535**	**0.040***	-0.822 to -0.032
Upward (+) GRF	12.57 ± 2.50	**-0.579**	**0.024***	-0.842 to -0.095
Joint moment (Nm/kg)				
Ankle plantarflexion (-)	-1.58 ± 0.22	**0.548**	**0.034****	0.050 to 0.828
Hip extension (-)	-0.72 ± 0.61	0.424	0.115	-0.113 to 0.769
Joint power (W/kg)				
Ankle positive (+)	6.43 ± 2.64	**-0.788**	**< 0.001*****	-0.926 to -0.462

Mean ± standard deviation.

*p < 0.05, **p < 0.01, ***p < 0.001.

Table 4-2 . Peak kinetic variables for the pivot leg and their correlation with the sweeping leg velocity at sweep contact

Variable	**Mean ± s**	**r**	**p**	**95% CI**
Ground reaction force (N/kg)				
Posterior (-) GRF	-3.31 ± 0.62	0.485	0.067	-0.036 to 0.799
Moment (N/kg)				
Clockwise (+) rotation	2.14 ± 0.33	**-0.604**	**0.017***	-0.853 to -0.133
Joint moment (Nm/kg)				
Knee extension (-)	-1.99 ± 0.62	**0.602**	**0.018***	0.130 to 0.852
Hip flexion (+)	1.88 ± 0.42	**-0.589**	**0.021***	-0.846 to -0.111
Joint power (W/kg)				
Knee positive (+)	3.18 ± 2.01	**-0.745**	**0.001****	-0.910 to -0.377
Hip positive (+)	6.26 ± 3.02	-0.448	0.094	-0.781 to 0.083

Mean ± standard deviation.

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

4.4. DISCUSSION

This study aimed to determine the kinetics of the lower limbs during the execution of osoto-gari and investigate the relationship between relevant kinetics variables and the sweeping leg velocity at sweep contact.

After the pivot leg left the ground, the forces acting on the tori's sweeping leg increased in the anterior and upward directions. However, these forces only produced a small clockwise moment. This was due to the resultant moment arm being short (r_s; shown in Figure 4-2(a)). Osoto-gari is a forward-throwing technique (view from the tori), and larger forward momentum of the body must be generated before the throw to achieve the best throw. Obviously, the goal of the sweeping leg action during the mid-swing phase is mainly to push the CoM of the tori forward quickly (Figure 4-4 (f)). The statistical results revealed that the peak anterior force and the upward force of the sweeping leg were significantly correlated with the sweeping leg velocity at sweep contact (Table 4-1). We considered that the black belt judokas may produce greater forward CoM momentum through the sweeping leg pushing the ground and transmitting the momentum to obtain a high sweep velocity at sweep contact.

The peak ankle plantar flexion moment of the sweeping leg was significantly correlated with the sweeping leg velocity at sweep contact, whereas the hip peak extension moment was not (Table 4-2). The sweeping leg ankle plantar flexion moment was dominant before the sweeping leg was off the ground (approximately 60% normalised time) (Figure 4-5). Furthermore, the sweeping leg ankle plantar flexors exerted a positive joint power during the mid-term swing phase, suggesting that the ankle plantar flexor muscles were activated concentrically. Additionally, the peak positive power was significantly correlated with the sweeping leg velocity. Based on these results, it can be said that the black belt judokas rely mainly on exertion of the sweeping leg ankle plantar flexor muscles to generate GRF that pushes the CoM of the whole body forward, which also may indirectly contribute to an increase in sweeping leg velocity at impact.

From the time the pivot leg touched the ground (approximately 50% normalised time) through the late swing phase, the GRF resulted in a progressively larger clockwise moment (Figure 4-6 (e)). This was because the resultant moment arm (r_P; shown in Figure 4-2(b)) was long. The time-series pattern of the anterior/posterior moment arm (Figure 4-6 (c)) showed that the moment arm was in the anterior (+) direction in the mid-late swing phase and then in the posterior (-) direction starting at the beginning of the throwing phase. The anterior/posterior moment arm value ranged from + (anterior) to – (posterior), implying that, from a mechanical perspective, the resultant moment arm became long and contributed to the production of the clockwise moment. Our statistical results revealed that the peak clockwise moment was significantly correlated with the sweeping leg velocity (Table 4-2), which supported the first hypothesis of this study. Taking a closer look at the external moment (Figure 4-6(e)) and trunk inclination angular velocity (Figure 4-6(f)), as the external moment increased constantly in the clockwise direction starting at 65% normalised time, the angular velocity of the trunk quickly rotated to the forward direction. This result is consistent with that described in the Introduction; the external moment about the CoM can strongly promote the rotation of the trunk and drive the distal segments together, which may have a role in accelerating the reaping of the sweeping leg.

The peak knee extension moment and the peak hip flexion moment of the pivot leg were significantly correlated with the sweeping leg velocity at sweep contact (Table 4-2). The pivot leg knee extension moment plays a primary role in braking, preventing the body from falling forward when the sweeping leg is about to contact the uke’s lower limb. For the pivot leg hip flexion moment, the peak value appeared at approximately 100% normalised time when the tori's sweeping leg was ready to reap backward (Figure 4-7(f)). When the pivot leg touched the ground, the moment arm displayed a positive value, which means that the CoP of the pivot leg was in front of the CoM (Figure 4-6(c)), resulting in a slight counterclockwise moment being generated at the later part of the swing phase (Figure 4-6(e)). This moment forces the trunk to rotate backward and is not beneficial to the execution of the leg sweep. Thus, we speculated that the hip flexors were contracted to resist the counterclockwise moment and maintain a stable trunk position in which the sweeping leg could easily sweep.

For pivot leg joint power, the hip flexors exerted the largest positive power, followed by the knee extensors at sweep contact, suggesting that the knee extensor and hip flexor muscles were activated concentrically. The peak positive power of the pivot leg knee joint was significantly related to the sweeping leg velocity. However, the peak positive power of the pivot leg hip joint was not (Table 4-2). The positive power exerted at the pivot leg knee joint could generate more kinetic energy and transmit it to the sweeping leg via the pelvis, helping build an effective kinetic chain that could render a powerful sweeping action. On the other hand, we considered that extension of the knee extensors might result in pressure being applied against the ground, causing the GRF of the pivot leg to increase continuously in the upward direction (Figure 4-6(b)) beginning at 100% normalised time. As previously mentioned, a long moment arm can facilitate moment generation; in fact, increasing the upward component of an external force can also facilitate moment generation from a mechanical perspective. Although the pivot leg hip flexors exerted greater positive power in the throwing phase, anatomically, a hip flexion moment induces the lower trunk forward tilt. Thus, we considered that positive pivot leg hip power might be a primary contributor to good upper body-to-upper body contact, rather than to leg sweeping. Thus, the second hypothesis was mostly supported.

Figure 4-6 shows time-series data for the sweeping leg knee joint angle in 15 participants. Kuo (2001) indicated that knee-flexed-style leg sweeping is more efficient and powerful than knee-extended-style sweeping. Therefore, we considered that the leg sweeping style may affect the leg sweep velocity at impact. As a result, the maximum angle of the sweeping leg knee joint appearing at 101% normalised time (black vertical line) was 146 degrees, and the minimum angle was 89 degrees. Then, the maximum angle of the sweeping leg knee joint appearing at sweep contact (black vertical dashed line) was 137 degrees, and the minimum angle was 98 degrees. It is obvious that the sweeping leg style depended on the preferences of the participants. In future work, this issue should be addressed.

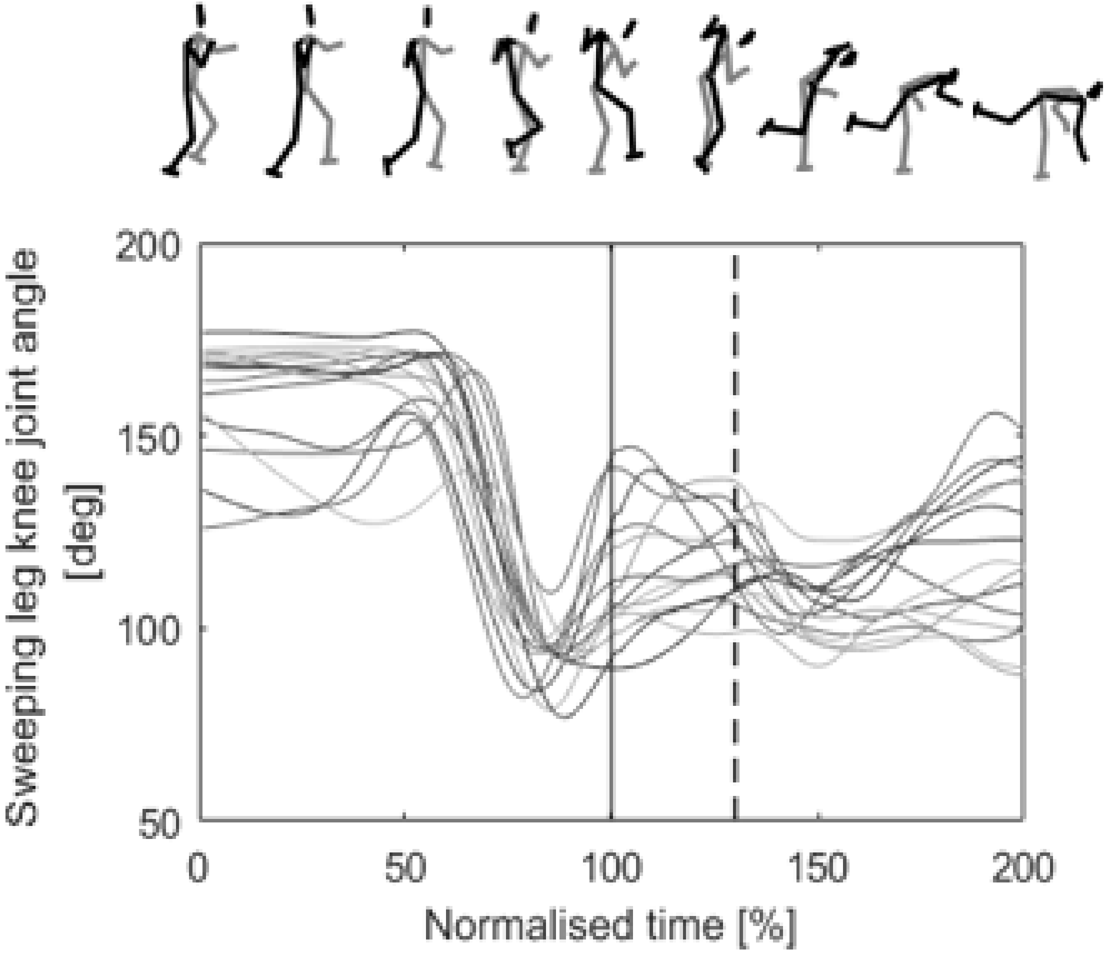

Figure 4-6. Time-series data for the sweeping leg knee joint angle in 15 black judokas.

Vertical dashed line (black): the instant of sweep contact.

4.5. CONCLUSION

In summary, skilled male judokas can achieve a higher leg sweep velocity at sweep contact by effectively using GRFs generated by exertion of the lower limb joints. For the sweeping leg, the peak anterior and upward component forces were significantly correlated with the peak sweeping leg velocity at sweep contact. In addition, the peak ankle plantar flexion moment and positive power were significantly correlated with the peak sweeping leg velocity at sweep impact. The findings suggest that skilled male judokas increase momentum of the whole body in the forward direction during the swing phase mainly through the exertion of the ankle plantar flexor muscles, which indirectly increases the sweeping leg horizontal velocity at impact. In the mid-term throwing phase, the peak clockwise external moment and the peak knee positive power of the pivot leg are also correlated with the leg sweeping velocity. These results suggested that increasing the clockwise moment promoted forward rotation of the whole body through extension of the pivot leg knee joint, which is a crucial biomechanical factor in increasing the velocity of the sweeping leg at sweep contact. The findings also suggest that the knee joint extension moment and the flexion moment of the pivot leg may control body balance, which can benefit the execution of the leg sweeping motion.

CHAPTER 5

5.1. GENERAL DISCUSSION

The purpose of this study was to identify technical factors and approaches to improve the performance of osoto-gari from a kinematic and kinetic perspective. The results of the kinematic and kinetic studies on osoto-gari from Chapters 3 and 4 will be comprehensively discussed in this chapter.

In previous studies, most studies on the osoto-gari throwing technique used biomechanical analysis to examine the sweeping leg. Although some studies have elaborated on the upper body pushing action, due to measurement limitations, the upper body action was only examined in the sagittal plane. Most of these studies also separated the action of the upper body from that of the sweeping leg for the analysis. However, all judo throwing techniques are based on the efficient use of every part of the body. Thus, these studies are insufficient and can only provide a limited understanding of osoto-gari. Therefore, in Chapter 3, we investigated the characteristics of the action and the relationship and coordination of the upper body and swinging leg in osoto-gari by comparing the motion patterns of black belt and white belt judokas.

It was found that during the swing phase, the black belt judokas had larger peak angular velocities of the arms and trunk than the white belt judokas. These results suggest that the black belt judokas might break the uke's balance by pulling the uke's upper body before throwing. In judo, *kuzushi* "崩し" is an important skill that controls or disrupts the opponent's posture and balance. Because the human body is very heavy when standing in a balanced position, it is difficult to rotate the opponent's body directly. This suggests that the black belt judokas pull the opponent's upper body to force the opponent to resist in the opposite direction and then take advantage of the resistances to execute the throw. This series of actions can also be called *hando kuzushi* “反動崩し”, which involves the use of countermovements to disrupt an opponent's balance. We also found that the timing of the peak values for the thigh and shank of the sweeping leg in the black belt judokas was later than that in the white belt. These results suggested that the black belt judokas intentionally delay the swing of the sweeping leg, which aids in storing strength or energy to better build the kinetic chain for the leg sweep.

During the throwing phase, the black belt judokas had substantially greater peak angular velocities of the arms, upper torso, and trunk twist during the throw. Additionally, the timing of the peak velocity of the upper torso and trunk twist of the black belt was closer to sweeping leg contact than that of the white belts. These results indicated that the upper body pushing and leg sweeping actions of the black belt judokas were executed simultaneously during the throw, reflecting the good whole-body coordination of the black belt judokas. These skill differences between the black and white belt judokas also explains why the black belt judokas can create a large angular momentum in the uke’s upper body and leg, enabling them to rotate the uke’s body more effectively than the white belt judoka. Good whole-body coordination can also reduce the time required for throwing. In practice, it can considerably increase the success rate of the technique.

Given this information, to produce a powerful osoto-gari, the thrower should pay more attention to the coordination and relation of the reaping and pushing actions than to the reaping action of the sweeping leg. In addition, it is necessary to use countermovements, such as pushing or pulling, to increase the effectiveness of the throw.

Chapter 4 investigated the characteristics of the GRF, the external moment, the lower limb joint dynamics, and the association of these kinetic variables with the sweeping leg velocity at sweep contact in black belt judokas.

During the swing phase, the anterior and upward component forces acting on the sweeping leg were greater, and both peak values were significantly correlated with the peak sweeping leg velocity. In the pre-mid-term swing phase, the sweeping leg pushes the whole body forward. The findings showed that the skilled judokas could generate a larger forward momentum by pushing the ground and then transferring the momentum to the distal segment, indirectly accelerating the leg sweep's velocity. Furthermore, the sweeping leg ankle joint exhibited a larger plantar flexion moment and positive power due to the action of the ankle plantar flexor in the mid-term swing phase. The peak values of both variables were also significantly correlated with the peak velocity of the sweeping leg. From these results, the skilled judoka would rely on exertion of the ankle plantar flexors of the sweeping leg to generate the GRF and push the tori's CoM forward quickly, which would increase the sweeping leg velocity at sweep contact. Therefore, we recommend maximizing or strengthening the sweeping leg ankle plantar flexor contraction during the middle of the swing phase to generate high sweeping leg vorticity.

After the pivot leg touches the ground and beginning at the latter part of the swing phase, the anterior/posterior and vertical GRFs of the pivot leg generate a large clockwise moment about the CoM. The larger clockwise moment causes the upper body to turn forward quickly and then drive the sweeping leg leg together, ultimately increasing the velocity of the sweeping leg. Our statistical results also support this view. Therefore, we recommend that toris increase their external moment to obtain a higher leg sweep velocity during a throw, rather than rely on the effort of the sweeping leg only.

In terms of joint moments, the pivot leg knee joint and hip joint generated a larger extension moment and flexion moment, respectively, from the latter part of the swing phase to the mid-late part of the throwing phase. In addition, both peak values exhibited a significant correlation with the peak sweeping leg vorticity. These joint moments can maintain body stability and indirectly aid in executing leg sweeping. As the osoto-gari technique is a throwing technique performed during single-leg standing, it is very important to maintain the balance of the body by controlling the lower limb muscles. It is also important to note the positive power due to the knee extension moment during the throwing phase. The peak positive power of the sweeping leg knee appeared almost simultaneously with sweep contact and was significantly correlated with the peak sweeping leg vorticity. The positive power exerted at the knee joint can not only provide kinetic energy for the distal segment but also increase the GRF to produce a larger external moment and generate a greater sweeping leg velocity in black belt judokas. Therefore, the results obtained in this study are expected to contribute to a better understanding of the mechanics of osoto-gari and improve performance of the sweeping technique.

In this study, biomechanical methods were used to elucidate the technical factors and approaches of osoto-gari to ultimately improve performance of the technique. These results obtained via rigorous biomechanical analysis can help judo practitioners, especially beginners, understand the characteristics and principles of the action so that they can master osoto-gari quickly and effectively. Additionally, the results offer useful insights for instructors in the judo community and are of value to the academic community.

5.2. LIMITATIONS

The osoto-gari throw was performed in an indoor laboratory, and the uke wore a specially designed judo suit in which only the sleeves and collar to ensure that the reflective markers attached to his body could be captured clearly. Previous studies (Ishii et al., 2018; Koshida et al., 2017) used the same method to assess the judo throwing technique; they pointed out that the motion data obtained in a limited measurement environment might be different from those obtained in a real grappling situation. Due to technical limitations, however, the specific differences caused by using a regular judo uniform versus a special judo uniform cannot yet be assessed quantitatively. In Chapter 3, although the height and mass of the two groups were matched, each thrower's muscle strength or power could be different. The thrower relies not only on technique but also on muscle strength, which is an important factor in creating a large angular momentum in the uke's upper body. In Chapter 4, the difference in sweep leg style executed by each thrower who participated in this study was not considered. The use of different types of leg sweeps may affect the peak leg sweep velocity at impact. The external moment around the CoM of the tori was calculated using only the external force generated by the tori's leg that was in contact with the ground; however, the external force from the uke, such as resistance or friction, was not measurable with the experimental equipment in this study. Finally, to understand the muscle exertion characteristics of the tori's lower limb joint, we used the conventional Newton-Euler method. This approach does not provide specific information on individual muscle activity or function during joint movement.

5.3. FUTURE STUDY

The main participants of this study were university judo team members at the black belt level and university students who were not at a black belt level. In the future, more categories and levels of judokas, including top-class black belt judokas and even female judokas, should be analysed. In addition, the measurement was performed without resistance from the uke. Judo is a two-person combative sport; the uke's behaviour may have considerable influence on the tori's action or throwing strategy. Thus, in future studies, the measurements should be performed in with the uke in different postures (a neutral posture, a defensive posture, and a forward bent posture) to increase the difficulty of the throw, as in Deguchi et al. (2018). This finding would be helpful in teaching efficient execution of osoto-gari in judo practice.

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