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INTEGRATED BIOMECHANICAL MODEL FOR ASSESSING EXPLOSIVE STRENGTH THROUGH INTERNAL AND EXTERNAL FORCE IMPULSES

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Abstract

Explosive strength is a key physical quality in judo, where athletes must generate rapid, coordinated whole-body impulses to destabilize, lift, or rotate an opponent during the phases of *kuzushi*, *tsukuri*, and *kake*. Understanding the biomechanical mechanisms that support these actions is essential for optimizing technical execution and improving performance. The present study investigates the kinematic and dynamic characteristics of explosive strength using the vertical jump as a model movement, as it reflects the sequential activation, joint coordination, and torque development required in many judo techniques. The ***aim*** of the study is to identify the relationship between the kinematic structure of the human body and the torque moments generated in individual joints during explosive movement, and to determine how these mechanisms contribute to effective impulse production relevant to judo performance. The methodology combines video-based motion analysis with measurements of external support reactions, enabling the calculation of joint torques, segmental centers of mass, and inertial characteristics. The symmetrical nature of the vertical jump allows the movement to be modeled with eight segments, ensuring both analytical precision and biomechanical relevance. The ***results*** show a clear sequential activation pattern in the lower limbs, with strong intermuscular synergy between the metatarsophalangeal, ankle, knee, and hip joints. Distinct torque profiles were observed across joints, reflecting their specific functional roles in stabilizing the body and generating vertical impulse. The upper limbs demonstrated harmonic, well-timed torque development, indicating their contribution to optimizing whole-body dynamics during explosive movement. Verification of the calculated values through direct measurement of support reactions confirmed the reliability of the method, with an acceptable error margin. The ***discussion*** highlights the relevance of these findings to judo, where efficient force transfer, coordinated segmental interaction, and precise timing are essential for effective execution of throws. The observed torque patterns mirror the demands of judo techniques that require rapid upward or rotational acceleration. The study emphasizes the importance of integrated biomechanical analysis for understanding how different joints contribute to impulse generation and how these mechanisms can be enhanced through targeted training. In ***conclusion,*** the vertical jump provides a valid and informative model for examining explosive strength in judo. The identified torque patterns and segmental interactions offer valuable insights for improving technical performance, refining training strategies, and supporting evidence-based preparation of judo athletes.

1. Introduction

Explosive strength and coordinated whole-body movement are essential components of effective judo performance, particularly during the phases of *kuzushi*, *tsukuri*, and *kake*, where athletes must generate rapid impulses, maintain balance, and manipulate the opponent's center of mass. The biomechanical foundations of such movements are grounded in classical theories of motor control and coordination (Bernstein, 1967; Chkhaidze, 1962; Fitts, 1954), which describe how the neuromuscular system organizes complex actions through hierarchical regulation and efficient force transfer. Contemporary models further emphasize the role of movement variability, segmental synergy, and adaptive control in skilled performance (Schmidt & Lee, 2011; Latash, 2008).

Within the context of judo, these principles are directly reflected in the technical and philosophical foundations established by Kano (2013), who emphasized efficiency, balance, and optimal use of energy. Modern scientific analyses of judo performance confirm the importance of explosive strength, neuromuscular coordination, and whole-body integration. Physiological profiling of elite judo athletes demonstrates high demands on power production, anaerobic capacity, and rapid force development (Franchini et al., 2011). Biomechanical studies of judo techniques further show that effective execution depends on precise control of the center of mass and coordinated activation of multiple joints (Imamura et al., 2006). Reviews of strength and power assessment in judo highlight the relevance of evaluating explosive actions, such as vertical jumps, as indicators of technical readiness and performance potential (Detanico & Santos, 2012).

Although several referenced works focus on wellness, health promotion, and physical development (Aleksandrova, 2021; Dimitrova, 2024; Dimitrova & Nesheva, 2021; Dimitrova et al., 2018; Dimitrova et al., 2020; Dimitrova & Tomova, 2025; Popova Dobreva, 2023), they collectively reinforce the importance of structured physical activity, functional movement, and individualized approaches to training—principles that align with the demands of judo practice and athlete preparation.

Biomechanical analyses of human movement (Kulikov, 1984) provide a scientific basis for understanding how joint torques develop during explosive actions such as jumping, lifting, or rotational acceleration. The vertical jump, in particular, is widely used as a model for assessing explosive strength because it involves coordinated activation of multiple joints and segments, mirroring the whole-body dynamics required in judo throws. By integrating kinematic and dynamic data, it becomes possible to evaluate segmental contributions, torque distribution, and intermuscular synergy—key factors in optimizing technical execution.

Taken together, the existing literature supports the need for an integrated biomechanical approach to understanding explosive strength in judo. By analyzing the kinematic and dynamic characteristics of a vertical jump, this study aims to identify the joint torque patterns and segmental interactions that underpin effective impulse generation, offering insights relevant to performance enhancement and technical refinement in judo.

2. Methods

2.1. Objective

The aim of the present study is to reveal the relationship between the kinematic and dynamic structures involved in the manifestation of explosive strength, with a specific focus on its role in judo techniques. Based on this relationship, the study seeks to determine how the internal force field contributes to the generation of an effective impulse during key technical actions in judo, where rapid force production, coordinated segmental interaction, and precise timing are essential for successful performance.

2.2. Methodology

The methodology combines two complementary analytical approaches designed to capture the specific characteristics of explosive strength in judo.

First, a video-based motion analysis system was used to record the kinematic parameters of the main body segments. This method enabled the determination of segmental centers of mass, joint angles, angular velocities, accelerations, and the calculation of torque moments in key joints. Such an approach is particularly relevant to judo, where techniques rely on coordinated lower- and upper-limb actions and rapid shifts of the center of mass during phases analogous to kuzushi–tsukuri–kake.

Second, external force data were collected using a dynamographic platform, which measured ground reaction forces and the temporal structure of the movement. Specialized software was used to synchronize the kinematic and dynamic data and to analyze the interaction between internal muscle moments and external force impulses. This made it possible to evaluate how individual joints contribute to the generation of an effective impulse during movements similar to those used in throws such as seoi-nage, o-goshi, uchi-mata, and harai-goshi.

2.3. Organisation

The study was conducted under controlled laboratory conditions with national-level judo athletes to ensure high technical consistency and practical relevance. Each participant performed 30 standardized trials of an explosive strength test, allowing reliable assessment of movement variability and individual execution patterns. Kinematic and dynamic data were recorded simultaneously and later synchronized for integrated analysis. This organization ensured a consistent experimental environment and provided a solid basis for identifying the segmental contributions, timing characteristics, and individual technical features that influence explosive performance in judo.

3. Results

The software developed for solving the direct biomechanical problem made it possible to obtain numerical values of the static forces arising as support reactions on the individual joints, as well as the muscle torque moments for each of the designated kinematic pairs (Fig. 1).

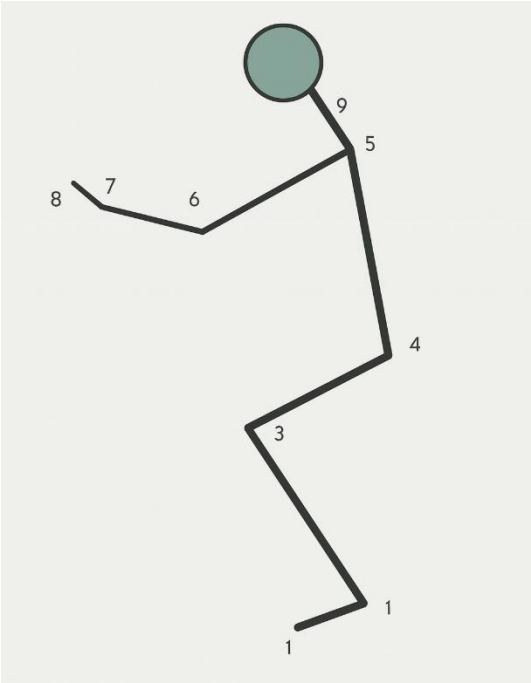


Fig. 1. Joint Reaction Forces and Torque Moments

Since the movements of the limbs during the explosive strength test (vertical jump) are completely symmetrical, the segments in the kinematic chain can be reduced to eight. On this basis, the spatial characteristics of the segmental and total centers of mass, as well as the inertial force parameters, were calculated. Due to objective instrumental limitations of the video-computer method, related to the resolution of the recorded image, the results were verified through direct measurement of the external support reactions. The combined approach demonstrated that the overall error does not exceed 7.5%. Theoretical analysis indicates that a significant part of this error originates from the use of a unified human body model. It can be minimized by experimentally determining the individual centers of mass and segmental masses for each subject.

Figure 2 presents a typical distribution of the muscle torque moments relative to the lowest support point (metatarsophalangeal and knee joints). In the first case, the torque is not the result of the action of a specific muscle group passing through the axis of rotation, since the foot is the terminal segment of the kinematic chain. The two torque curves show comparable magnitudes and a similar temporal pattern. All kinematic segments located above them influence their development. Deviations in intermuscular synergy are observed at the beginning (frames 2–5) and at the end of the support phase (frames 10–11). Quantitatively, differences in rhythmic structure can be defined, with the knee joint demonstrating shorter temporal intervals.

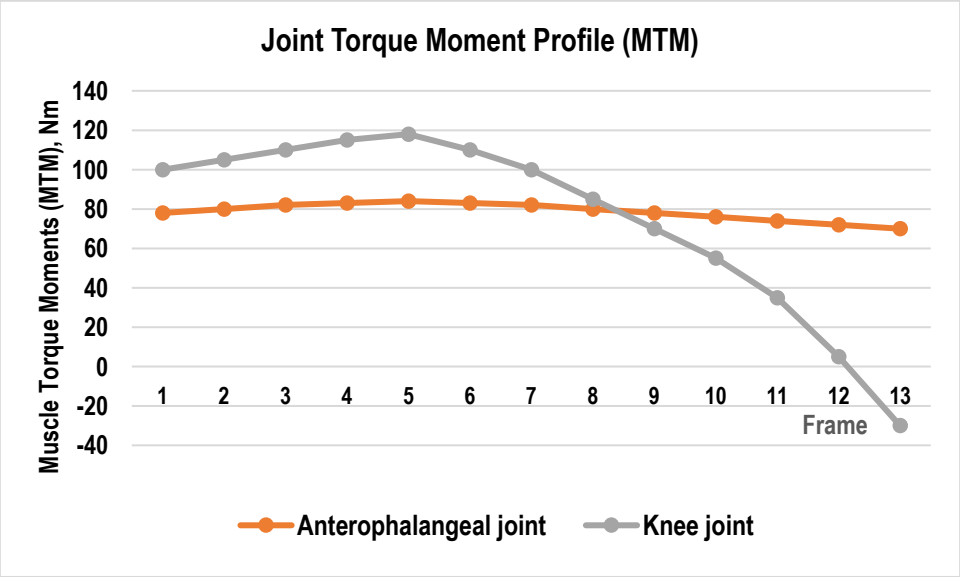


Fig. 2. Temporal Distribution of Muscle Torque Moments in the Support Phase

Figure 3 shows the torque moments in the ankle and hip joints. Significant differences are observed in the positions of the local and global extrema, especially in frames 4, 5, and 6. According to these biomechanical characteristics, similarities can be found between the knee and hip joints (frames 4–5), as well as between the

ankle and metatarsophalangeal joints (frames 5–7). Despite the high gradient of the torque at the beginning of the flight phase, its absolute value remains substantial.

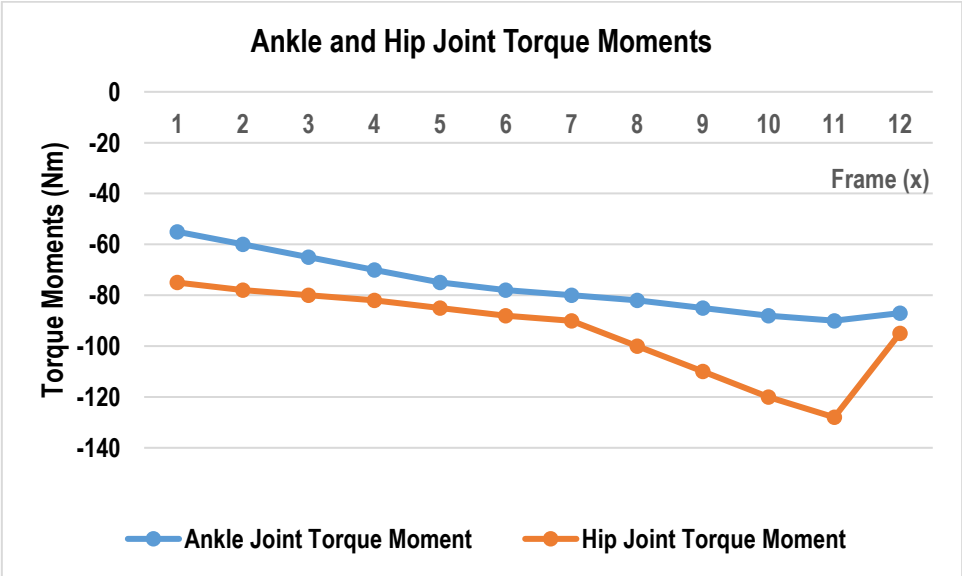


Fig. 3. Joint Torque Moments: Ankle vs. Hip

Figure 4 presents the muscle torque moments in the shoulder, elbow, wrist, and atlanto-occipital joints. The development of the biomechanical indicators in the upper limbs is harmonic (sinusoidal), with clearly expressed and coinciding local and global extrema: maxima in frame 4, minima in frame 10, and an inflection point in frame 7. Regarding the maximum values, synergy can be observed with the activity of the ankle joint, while the minima correspond to the metatarsophalangeal joints. The contribution to the overall superposition of torque moments progressively decreases from the shoulder joint to the atlanto-occipital and wrist joints.

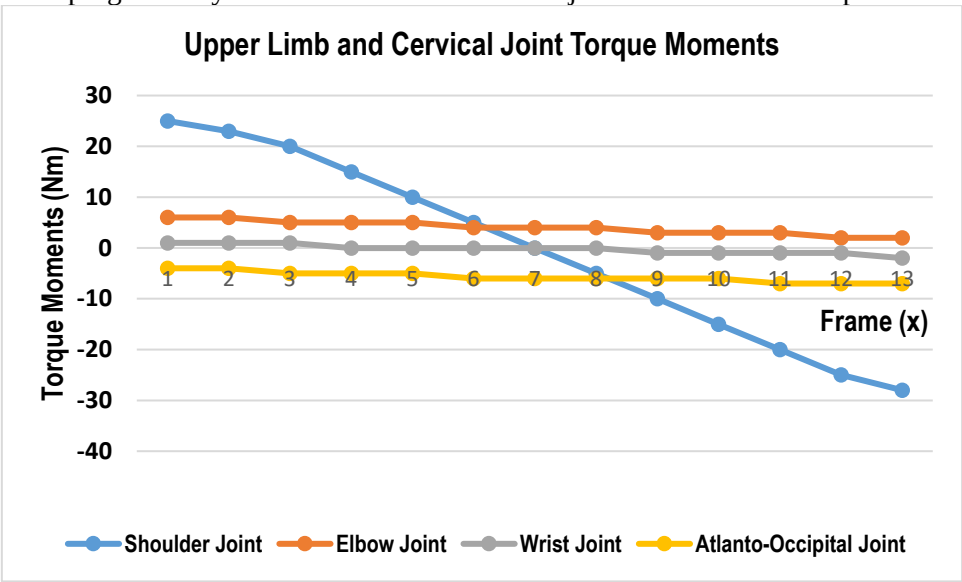


Fig. 4. Torque Moments of the Shoulder, Elbow, Wrist, and Atlanto-Occipital Joints

To complement the graphical representations in Figures 1–4, Table 1 summarizes the key characteristics of the torque moments across the main joints involved in the explosive movement. The table highlights the temporal structure of the local and global extrema, the dominant torque patterns, and the specific functional contribution of each joint.

Table 1. Summary of Joint Torque Moment Characteristics

Joint Segment	Torque Pattern	Local Extremum (Frame)	Global Extremum (Frame)	Notes
Knee	Short intervals	4–5	10	Deviations in synergy
Ankle	High gradient	5–6	4	Strong impulse in flight phase
Hip	Similar to knee	4–5	6	Substantial torque
Shoulder	Sinusoidal	4	10	Synergy with ankle

The summarized data confirm several key biomechanical tendencies observed in the graphical results. The knee and hip joints demonstrate closely aligned temporal patterns, with local extrema occurring in frames

4–5, indicating synchronized contribution during the main propulsive phase. The ankle joint shows a distinct high-gradient torque profile, with an early global maximum (frame 4), reflecting its critical role in initiating the upward impulse. The upper-limb joints, particularly the shoulder, exhibit a harmonic sinusoidal pattern with maxima aligning with lower-limb activity, suggesting coordinated whole-body involvement in generating the explosive movement. These findings reinforce the importance of segmental synergy and timing in producing an effective impulse — a principle directly relevant to explosive actions in judo techniques.

4. Discussion

The results of this study demonstrate a clear relationship between the body's kinematic structure and the development of joint torque moments during a vertical jump, a movement that effectively models the explosive strength required in judo. The sequential activation of the lower-limb joints mirrors the biomechanical logic of the *kuzushi–tsukuri–kake* phases, where efficient force transfer from the ground is essential for throws such as *seoi-nage*, *o-goshi*, and *uchi-mata*. The symmetry of the movement allowed the model to be reduced to eight segments without loss of biomechanical accuracy.

Verification through direct measurement of support reactions showed good agreement with the calculated values, with an error below 7.5%. This highlights the importance of individualized anthropometric parameters, especially in judo athletes whose body proportions and technical styles vary across weight categories.

The torque distribution in the support phase revealed strong intermuscular synergy between the metatarsophalangeal and knee joints, reflecting their complementary roles in stabilizing the body and generating vertical impulse. Similar coordination is required in judo during explosive upward movements, particularly in the *tsukuri* phase of *seoi-nage*.

Differences between the ankle and hip joints emphasize their distinct contributions: the ankle controls the final push-off, while the hip provides the main vertical force—an interaction directly relevant to hip-dominant throws such as *o-goshi* and *harai-goshi*. The upper-limb torque patterns showed harmonic, well-timed activity, supporting the role of the arms in optimizing whole-body impulse during *kuzushi*.

Overall, the findings confirm that explosive strength relies on tightly coordinated segmental actions across the entire body—a principle fundamental to effective judo technique. The consistent torque patterns across joints highlight the value of integrated biomechanical analysis for improving performance, where explosiveness, coordination, and timing are decisive for success.

5. Conclusion

The findings of this study demonstrate that explosive strength is the result of a highly coordinated interaction between the kinematic structure of the body and the torque moments generated in individual joints. The vertical jump proved to be an effective model for analyzing these mechanisms, revealing consistent patterns of segmental synergy and temporal organization across the lower and upper limbs. These biomechanical characteristics closely parallel the demands of judo techniques, where rapid force production, precise timing, and whole-body coordination are essential for effective execution.

The results highlight the distinct yet complementary roles of the ankle, knee, and hip joints in generating vertical impulse, as well as the contribution of the upper limbs in optimizing whole-body dynamics. The synchronization of torque development across joints reflects the integrated nature of explosive actions, which is fundamental to phases such as *kuzushi*, *tsukuri*, and *kake*. The observed relationships underscore the importance of individualized anthropometric and functional assessment, particularly in judo athletes whose performance depends on efficient force transfer and segmental coordination.

Overall, the study confirms that an integrated biomechanical approach provides valuable insight into the mechanisms underlying explosive strength and offers a solid foundation for optimizing technical performance in judo. Understanding how joint torques develop and interact can support more targeted training strategies, enhance movement efficiency, and contribute to improved execution of complex judo techniques.

Note

Conflict of Interest: *No conflict of interest was declared by the author and the institution.*

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