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A longitudinal study on karate parallel punch and front kick biomechanics: performance indicators and the effect of training

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Abstract

This study characterized biomechanical development during karate skill acquisition through longitudinal motion capture analysis. Four novices received weekly instruction from a black belt, nidan Goju-ryu instructor over four months. Motion data for parallel punch and front kick techniques were collected across 32 sessions and compared with expert performance. Expert motion demonstrated consistent signatures: two-phase velocity patterns (moderate approach followed by explosive impact), high repeatability (r > 0.85), and late-stage peak timing (85-90% of movement). Novices improved in trajectory consistency, peak velocity magnitude, and movement repeatability over four months. However, the two-phase velocity profile, sharp acceleration patterns, and precise timing developed slowly. Front kicks were easier to learn than punches, showing higher expert correlations. Positional accuracy was less critical than velocity/acceleration patterns for technique effectiveness. Findings reveal differential learning rates across biomechanical features, with force timing acquisition lagging behind force magnitude development.

Karate, expertise, observation, quantitative study, performance indicators, motor learning

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1 Introduction

Training improves martial arts performance through increased accuracy, velocity, and force generation, but quantifying these improvements objectively remains challenging. However, understanding how biomechanical parameters change with practice (Tenenbaum & Eklund, 2007), and how novice data compares against expert data over time, would allow objective assessment of skill development. Focused evaluation of biomechanical metrics could transform training assessment from subjective observation to empirically-supported analysis.

Single sessions of physical activity have been shown to enhance motor learning and cognitive abilities. For martial art practitioners, they were found to have better motor control (Sanchez-Lopez et al., 2014), attentiveness (Donovan et al., 2006; Alesi et al., 2014), fatigue resistance (Chaabène et al., 2012), and mental well-being (Potoczny et al., 2022; Qasim et al., 2014). While these non-biomechanical studies are critical, they investigated only a single session of practice and not how practice changes movement over time, and do not focus on quantitative metrics.

Studies that focus on biomechanical-derived metrics attempt to quantify expertise by comparing expert movement against novice movement. These studies show that experts have higher task space accuracy, acceleration (Neto et al., 2013), spatial coordination (Vagner et al., 2021; Beranek et al., 2022), peak velocity and force (Donovan et al., 2006; Margaritopoulos et al., 2015; Szafrański & Boguszewski, 2015; Aguiar de Souza & Mattos, 2017) within a shorter time-length (Falco et al., 2009; Vagner et al., 2021) in hand strikes, kicks, or general extension/flexion activities. Experts have a higher recall rate of novel *kata* (karate choreographed sequences) that they encountered for the first time (Hodge & Deakin, 1998), as well as have better postural control (Filingeri et al., 2012) and balance (Vando et al., 2013; Hadad et al., 2020). However, these studies tend to focus on single time point metric extraction from performed actions or from expert scoring, and thus provide only snapshots of comparative data.

A more comprehensive approach is to analyze time series kinematic data over time and across training sessions. Expert and novice data were collected of taekwondo choreography (Dharmayanti et al., 2018), taekwondo kick trajectories (Wasik et al., 2021), and *kata* (Emad et al., 2020). However, these studies either limit biomechanical analysis or examine only single collection sessions. They do not observe how longitudinal training influences motion refinement and what biomechanical changes emerge over time. Understanding training-induced changes in movement patterns could provide insight into motor learning mechanisms and skill acquisition.

This study tracks four karate novices receiving regular instruction from a black belt instructor over four months. Motion capture data for parallel punch and front kick techniques were collected bi-weekly or monthly (32 sessions total) and compared against expert motion. The goal is to identify biomechanical indicators of skill acquisition, characterize expert movement patterns, and track longitudinal trajectories of novice skill development.

We hypothesized that novice karate motion would initially differ substantially from expert motion in biomechanical characteristics, but would progressively converge toward expert patterns over four months of guided instruction. Specifically, we expected novices to demonstrate improvements in trajectory consistency, velocity profile development, and overall technique effectiveness as measured through correlation with expert movement patterns.

2 Materials and Methods

Participants and Training Protocol

Four karate novices (2 male, 2 female, average age 23 years) with no prior karate training received 1 hour/week in-person instruction from a black belt karate instructor (1 male, black belt, nidan, 15 years practicing karate, 5 years teaching experience) over 4 months. The instructor also served as the expert reference for biomechanical comparison. Motions were demonstrated to students through a combination of verbal instruction and visual demonstration as well as manual intervention or manipulation to adjust limb positioning.

The instructor taught *goju-ryu* karate, one of the major traditional Okinawan karate styles. *Goju-ryu* emphasizes circular movements, breathing techniques, and a balance between hard (*go*) and soft (*ju*) techniques. The parallel punch and front kick techniques taught follow traditional *goju-ryu kihon* (basic techniques) principles, emphasizing proper body mechanics, hip rotation, and efficient energy transfer from the core to the extremities.

The weekly sessions were taught with a focus on progress from a martial arts perspective. The expert's primary goal is for the novices to achieve consistency while being safe and disciplined, and thus emphasized the dual focus on both sport and art. While 4 months is not enough time to reach expertise, it is possible to achieve consistent foundational progress required before moving up in ranks.

The main mechanism to enforce and assess consistency is the motion trajectories, in that the novice can consistently and accurately maintain force and speed of movement. While technique efficiency is also important, it is of secondary focus.

Two karate techniques were analyzed:

1) Front parallel punch (Figure 1), where participants stood with arms at their sides and feet shoulder width apart, then alternated punching forward with right and left hands toward the xiphoid. The motion consists of an extension phase where the fist follows a curved path forward while rotating to palm-down orientation at full extension, followed by a retraction phase returning the hand to the side.
2) Right front kick (Figure 2), where the participants started with arms up and legs staggered, then kicked forward with the right leg. The motion comprises four phases: (1) chamber, where the rear knee was brought up to hip height and bent 90° at the knee, (2) extend, which snapped the leg forward for impact, (3) retract the leg, then finally (4) the foot was placed back on ground.

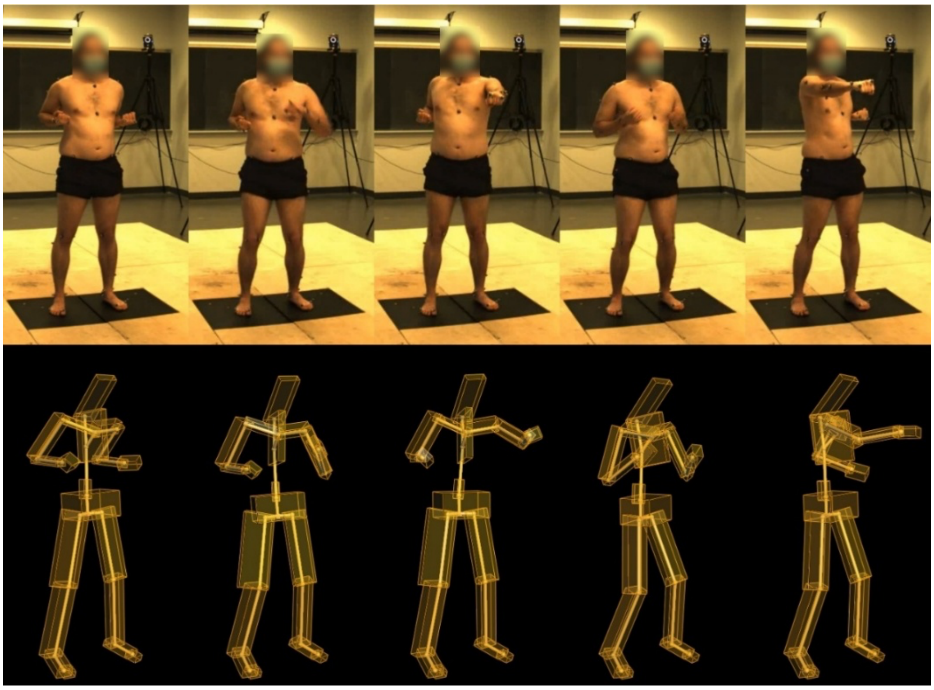

Figure 1*: Time lapse of the front parallel punch, showing optical camera (top) and Vicon motion capture reconstruction (bottom). This and all subsequent figures were created by the authors.*

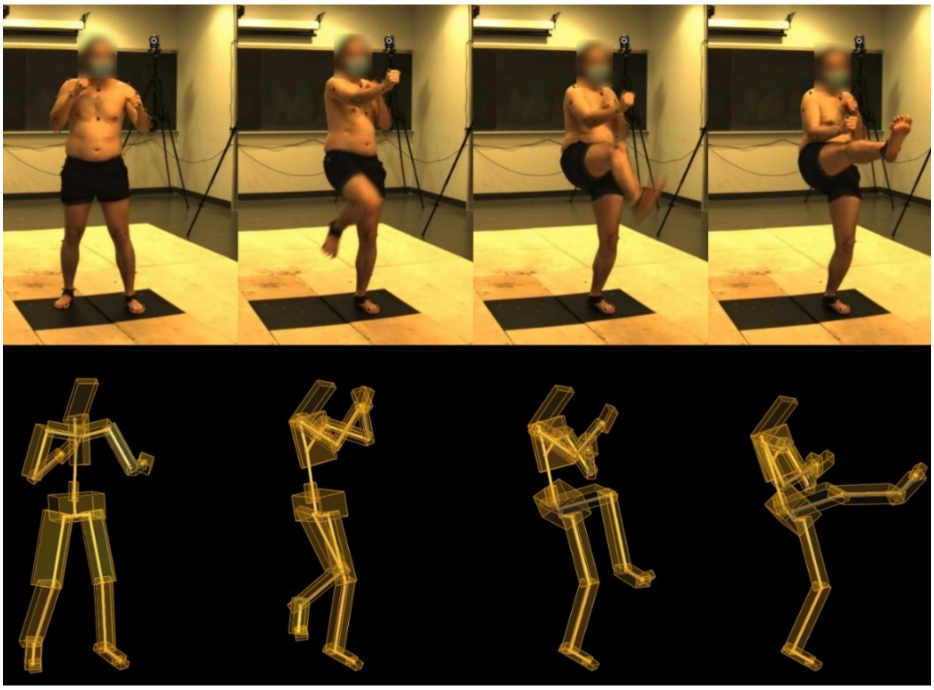

Figure 2*: Time lapse of the front kick (top), showing optical camera (top) and Vicon motion capture reconstruction (bottom).*

Motion Capture Data Collection and Processing

All 5 participants practiced karate movements during motion capture, on a bi-weekly schedule but adjusted for participant availability (Figure 3), over the span of 4 months, resulting in 32 sessions of data collected. At each of the 1 hour collection session, 5-10 repetitions of each motion were collected. All 5 participants are right-handed. Some participants had prior related experience in muay thai (Novice 1) and tricking (Novice 2).

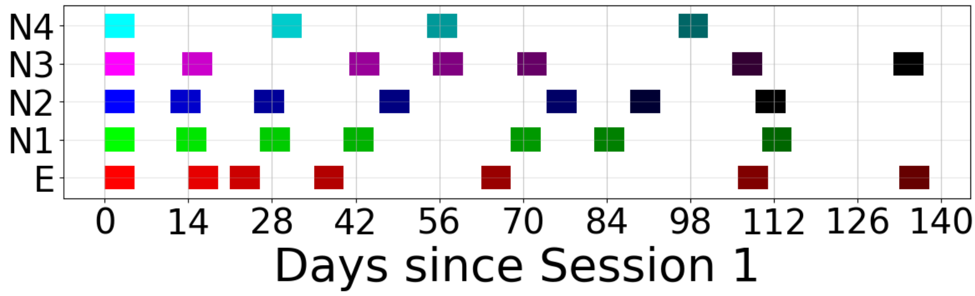

Figure 3: *Occurrences of data collection, where the x-axis is the number of days elapsed since the first data collection session, and the y-axis is the expert (E) or novice (N) participant ID. The colouring used is common to all figures in this paper, where the expert is red, and the novices are green, blue, purple, and cyan, respectively. Later sessions are denoted in a darker colour.*

The motion capture was facilitated by a 12-camera Vicon system (Vicon Nexus 2.14), utilizing the Istituto Ortopedico Rizzoli marker set (Leardini et al., 2007). The participants stood on marked flooring to control their heading, such that the forward, lateral, and vertical directions corresponded with the X, Y, and Z axis, respectively.

The joint centres of the collected motion capture data were calculated using BIORBD 1.8.7 (Michaud & Begon, 2021) and temporally segmented using zero-velocity crossings (Lin et al., 2016). For the parallel punch, where the right and left punch were executed sequentially, both right- and left-hand position were used to produce segments. For the right front kick, where only one side performed the action, only the right foot position produced segments.

Analysis

This paper focuses on the extension portion of the parallel punch and the right front kick. Segmented time series position, velocity, and acceleration data were temporally aligned such that full extension occurred at t=0. Mean and standard deviation of trajectories within each session were calculated by averaging over aligned repetitions. Sessions were then superimposed to visualize progression over time.

For parallel punches, hand Cartesian position, and elbow angles were analyzed. Zero position coordinate is centered at the xiphoid during the ready pose. For front kicks, foot Cartesian position and knee flexion angle were analyzed. Zero position coordinate is centered at the pelvis joint center.

Additional metrics calculated for each session included:

- Mean and standard deviation of movement extension execution time
- Mean and standard deviation of the final end effector position
- Absolute maximum velocity magnitude and timing (normalized 0-1, where 0 indicates maximum at motion start and 1 indicates maximum at motion end)
- Correlation of normalized joint center positions between novices and expert, and between novices and their own final session. Pearson correlation coefficients were calculated between

temporally normalized end effector position trajectories (interpolated to equal length via linear interpolation) for each session's mean trajectory. For novice-to-expert comparisons, each novice session was correlated with the last session of the expert. For novice self-consistency measures, each session was correlated with the participant's final recorded session to assess convergence toward their own developed movement pattern

Biomechanical comparisons were descriptive rather than inferential due to the small sample size and the high-dimensional time series nature of the kinematic data. Traditional parametric statistical tests were not appropriate for comparing multivariate movement trajectories. Instead, Pearson correlation coefficients quantified trajectory similarity, providing interpretable metrics of movement pattern matching between novice and expert motion.

3 Results

Because the goal of this study was to observe the effects of training on martial arts performance, analysis is framed around the key performance indicators defined by the instructor: internal consistency, task space accuracy and posture, speed and acceleration, and technique effectiveness. Both the parallel punch and front kick are analyzed using these indicators to interpret practitioner improvement.

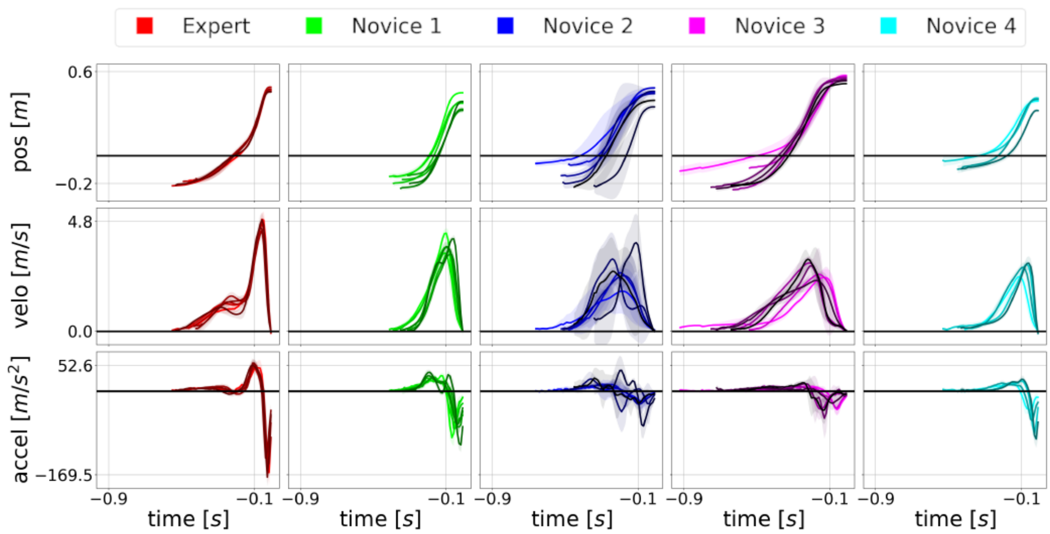

Figure 4: *Parallel punch hand position trajectories. (Top) Forward position. (Middle) Forward velocity. (Bottom) Forward acceleration. Mean trajectories with variance shaded bands for each participant across sessions. Lighter colors indicate earlier sessions, darker colors indicate later sessions. Expert (red) demonstrates high internal consistency with narrow standard deviation bands. Novices (all other colours) show progressive trajectory adaptation toward expert patterns, with consistency improving over training.*

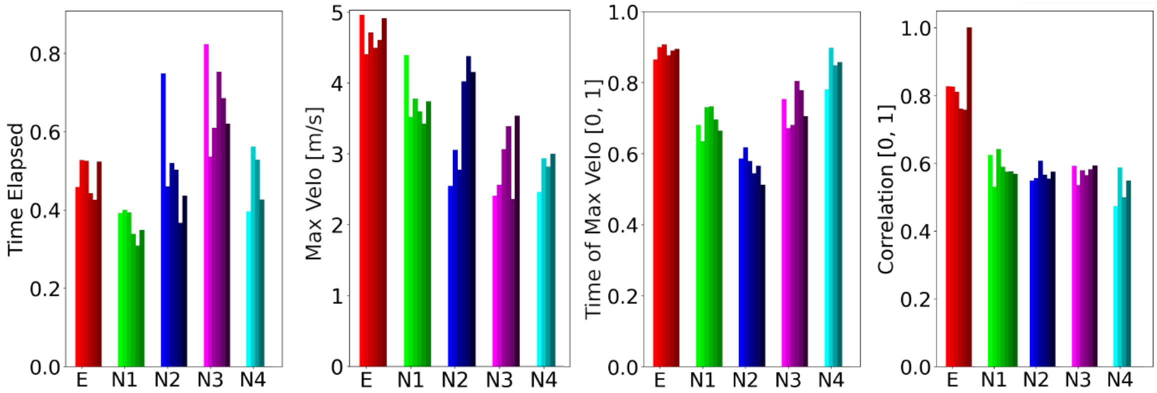

***Figure 5**: Parallel punch temporal and velocity metrics across training sessions. (Left) Mean execution time showing expert consistency versus novice variability. (Middle left) Peak forward velocity magnitude demonstrating modest novice improvement but persistent expert-novice gap. (Middle right) Timing of peak forward velocity (0=motion start, 1=motion end) showing expert consistently peaks late (~85-90% of movement) while novices progressively converge toward this timing pattern. (Right) Pearson correlation coefficient between novice and expert normalized end effector position trajectories showing novices remain substantially below expert self-correlation baseline (~0.85) throughout training.*

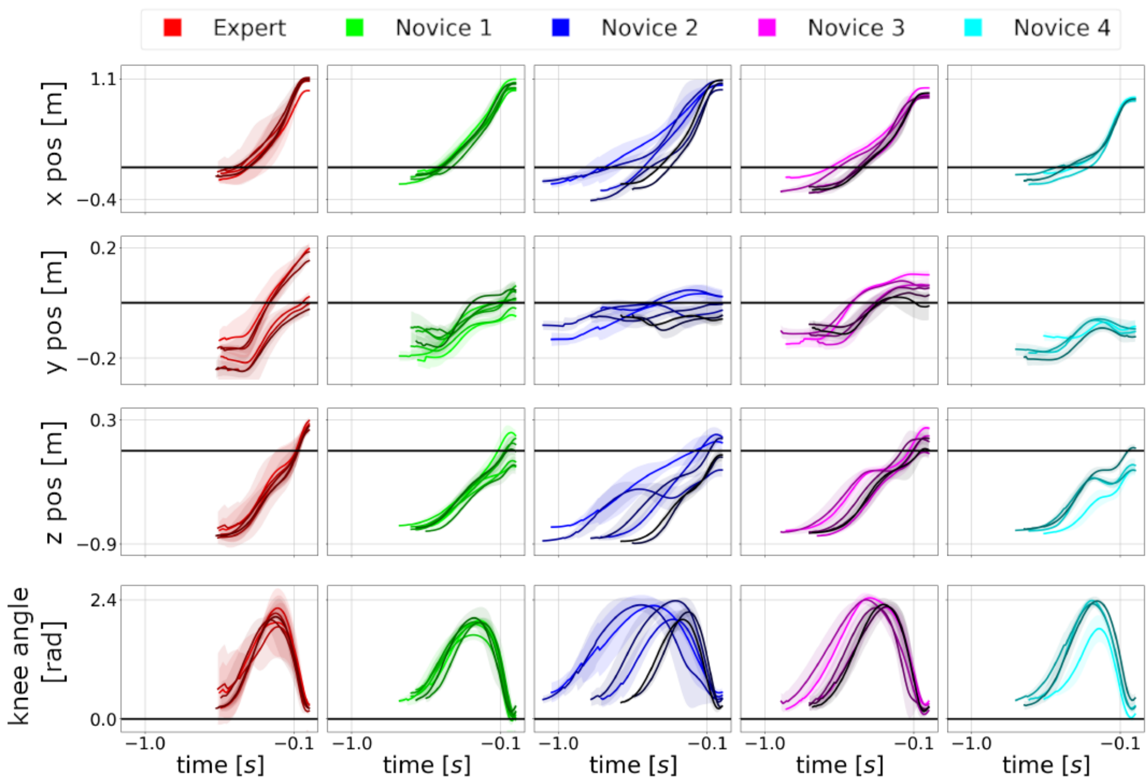

***Figure 6**: Front kick foot position trajectories and knee flexion angle. (Top left) Forward (X) direction showing velocity generation emphasis. (Top right) Lateral (Y) direction showing midline aiming. (Bottom left) Vertical (Z) direction showing height control. (Bottom right)*

Knee flexion angle demonstrating four-phase pattern: chamber at 90°, extend for impact, retract, return. Mean trajectories with variance shaded bands. Lighter colors indicate earlier sessions, darker colors indicate later sessions. Expert demonstrates wider variability than punch, suggesting multiple valid execution paths.

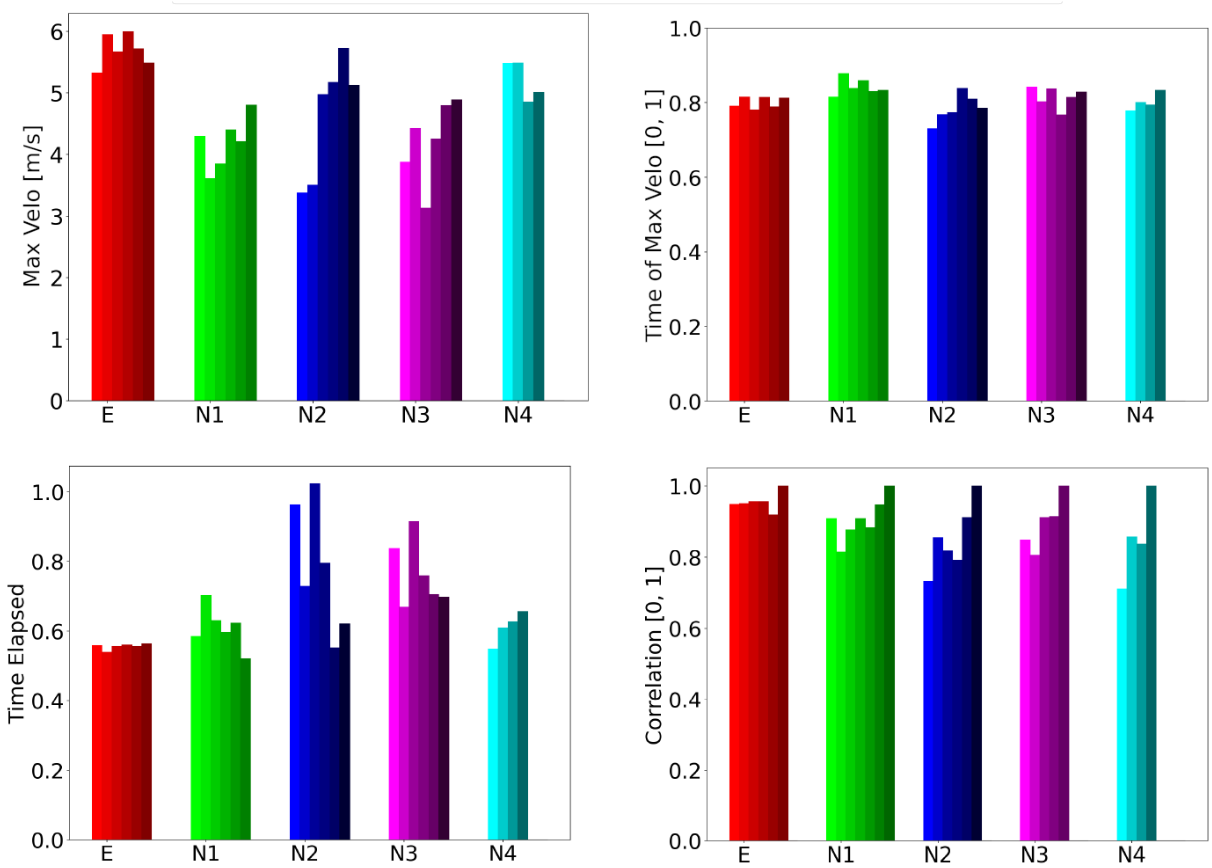

Figure 7*: Front kick temporal and velocity metrics across training sessions. (Top left) Peak forward velocity magnitude reaching approximately 6 m/s, substantially higher than punch velocities (~5 m/s, not shown). (Top right) Timing of peak forward velocity demonstrating expert pattern (~70-85% of movement) and novice convergence toward this timing. (Bottom left) Mean execution time showing expert maintains consistent timing while novice means vary. (Bottom right) Pearson correlation coefficient between each participant against their own last session, showing increasing convergence to their own movement over time.*

Internal Consistency

Expert motion demonstrates high internal consistency characterized by small standard deviation bands across repeated trials, with sharp and consistent velocity and acceleration peaks. Novice motion shows greater variability that gradually decreases over training sessions. For the parallel punch (Figure 4), the expert trajectory maintains consistent positioning, as did Novice 1, who had prior martial arts experience. The other novices initially displayed wider variation in trajectory application that progressively tightened over sessions as they converged toward consistent movement patterns.

Technique over-exaggeration, defined as excessive movements not primarily responsible for force generation, is characterized by: (1) elevated standard deviation in secondary joint rotational velocities relative to expert baseline, (2) asynchronous timing between primary and secondary movements, and (3) increased motion in non-primary planes.

In our data, over-exaggeration was most visible in elbow internal rotation, where Novices 1 and 2 exhibited broad, inconsistent acceleration peaks rather than the expert's sharp, controlled rotation spike, which is an injury risk. Comparison between left handed punch and right handed punch also show greater exaggeration on the left. Over-exaggeration diminished over successive sessions as novices developed proprioceptive awareness and core control, though some persistence in final sessions indicates extended practice is required for complete elimination.

For the front kick (Figure 6), expert standard deviation bands are wider than those observed in punching, particularly in the forward direction, suggesting the kick allows for more variation in execution path. Novice execution time shows high variability between sessions (Figure 7), whereas the expert maintains very consistent mean execution times, reinforcing that pattern consistency matters more than absolute values.

Task Space Accuracy and Posture

General trajectory patterns were successfully emulated by all participants across both techniques, with novice motion gradually adapting toward expert-like patterns over successive sessions (Figure 4Figure 6). Trajectory adaptation is particularly visible in kicking patterns (Figure 6), where the novices show clear convergence in forward motion, vertical motion, and knee angle trajectories toward the expert pattern. The temporal-positional alignment indicates participants are learning not just where to move, but when to move, which is critical for proper force generation.

In the parallel punch forward direction (Figure 4), expert motion showed a moderate velocity approach phase followed by sharp acceleration at impact, with novices gradually developing this two-phase pattern. In the lateral direction, later sessions show increased lateral accelerations in the novices without significant changes in positional accuracy, indicating growing confidence.

Vertical position analysis revealed considerable variation in both expert and novices despite instruction to "punch toward the xiphoid," with some novices punching as high as the chin. Final hand position data demonstrate that novices gradually reduce endpoint variability in the forward direction, though considerable variation remains in vertical and lateral directions.

For the front kick (Figure 6), forward direction emphasized velocity generation, lateral direction focuses on aiming toward the body's midline, and vertical direction shows patterns similar to forward movement. The knee flexion angle trajectory (Figure 6) shows novices learning the proper four-phase sequence: chamber at 90°, extend, retract, and return. Final foot position data reveals that expert lateral kick placement shows apparent variation due to center-of-mass shifting onto the supporting leg, which static coordinate analysis incorrectly classifies as error.

Importantly, final exact Cartesian positions and joint angles are not primary performance metrics according to the expert. Instead, the pattern of trajectory generation and visual appearance of force delivery matter more for individual strike effectiveness, as each practitioner has different physical capabilities.

Speed and Acceleration

Expert striking demonstrated a two-phase velocity pattern: moderate-velocity approach for trajectory aiming and postural adjustment, followed by sharp impact-phase acceleration reaching maximum velocity within 0.1 seconds of full extension. This sharp acceleration and velocity spiking is a key component of *kime*, which is the concentration of force delivery at the impact moment to maximize energy transfer.

For the parallel punch (Figure 4), this two-phase pattern was clearly visible in the expert's forward velocity curve but is generally absent in novice movement, with a notable exception in Novice 1's final session, where emergent two-phase velocity patterns became visible. All four novices increased their peak acceleration profiles in later sessions as training continued, yet the sharpness and timing of the velocity peak remained underdeveloped across all participants. Time taken to execute the punch (Figure 5) shows no obvious trend distinguishing expert from novice, suggesting that speed alone is not the defining characteristic. Rather, it is when and how that speed is applied.

Peak forward velocity timing (Figure 5) is consistently at 85% of the movement duration for the expert's right hand (ie peak occurs at 85% of the normalized movement time, close to full extension). Novices initially do not achieve this late peak timing, but over sessions their velocity peaks shift toward this range. Peak forward velocity magnitude (Figure 5) increases with time for all novices, indicating growing power generation capability.

For the front kick, the expert's velocity curve was smoother and more continuous, whereas novices show a more distinct velocity plateau between knee raise and leg snap phases, suggesting they initially treat the two parts as separate movements rather than a fluid sequence. Peak kick velocity reaches approximately 6 m/s, substantially higher than the 5 m/s achieved in punches (Figure 7).

Lateral direction velocity peaks occur during the middle portion of the kick, emphasizing that lateral movement serves aiming purposes, whereas forward direction velocity peaks toward the end to maximize impact force. Vertical acceleration should peak near full knee extension, then immediately stop to lock the leg straight. This pattern was not initially present in novice performance but emerged in later sessions across participants (particularly, Novice 1 and 4), demonstrating successful adaptation to instruction on proper leg extension and locking technique. Time taken to execute the kick (Figure 7) shows expert mean execution time is very consistent across sessions while novice means vary, reinforcing that consistency of technique pattern matters more than absolute speed.

Technique Effectiveness

To quantify overall technique similarity and improvement, correlation measures were calculated between normalized joint center positions. The expert demonstrates a baseline self-correlation of approximately 0.85-0.95 for punches and 0.90-0.95 for kicks (Figure 5Figure 7), indicating some natural variability exists even in expert performance and establishing a realistic upper bound for technique consistency.

For the parallel punch, novice movement compared to expert motion did not show meaningful increases over the four-month period, with correlations remaining substantially below the expert baseline (Figure 5). However, when novices are compared against their own final session, clear improvements are visible—later sessions correlate more strongly with the final session than earlier sessions do, indicating progressive skill development even if expert-level performance is not yet achieved.

For the front kick (Figure 7), novices show higher correlation to expert motion than observed in punching, suggesting the front kick is easier to master than the parallel punch. The higher correlation in kicking may be attributed to several factors. The kick has four distinct, teachable phases (chamber, extend, retract, return), whereas the punch requires more subtle nuances in hand rotation, chambering position, and force generation timing. Furthermore, lower limb musculature is substantially larger and may respond more readily to training within this relatively short collection period, whereas applying upper body fine motor control to generate high-impact striking requires significant relearning and refinement.

Overall, while novices do not achieve expert-level correlation within four months, measurable improvements are visible in self-consistency, trajectory pattern adaptation, and increasing velocity and acceleration profiles. Trajectory adaptation is evident in several novices (Figure 6), particularly Novices 2 and 3 (who initially displayed wide and varying technique application in early sessions), who show clear pattern merging toward expert motion in knee angle and forward foot position temporal patterns by later sessions. This demonstrates that the timing and sequencing of movement generation are being learned, which is critical for effective force delivery. These findings demonstrate that regular expert instruction produces observable biomechanical improvements, even over a relatively short training period.

Summary of Quantitative Findings

Table 1 summarizes key quantitative findings across the training period. Expert punches demonstrated peak velocity timing at 85-90% of movement with self-correlation of 0.85-0.95, while novices progressed from 40-60% of the movement and 0.40-0.60 correlation initially to 60-75% of the movement and 0.60-0.75 correlation after four months. Kicks showed faster convergence, with novices achieving peak velocity timing at 70-80% of the movement and 0.75-0.85 correlation by final sessions. The two-phase velocity pattern emerged in only 1 of 4 novices, confirming this as the most difficult feature to acquire.

***Table 1**: Summary of Key Biomechanical Metrics*

Metric	Expert	Novice Initial	Novice Final
Punch peak timing (%)	85-90	40-60	60-75
Punch correlation	0.85-0.95	0.40-0.60	0.60-0.75
Kick peak timing (%)	70-80	60-80	70-80
Kick correlation	0.90-0.95	0.70-0.80	0.75-0.85

4 Discussion

This longitudinal study identified distinct biomechanical characteristics of expert karate motion and tracked novice progression over four months of training. Analysis reveals that expertise is characterized by specific velocity and acceleration patterns, internal motion consistency, and adaptive variability in task space execution.

Table 2: *Comparison of expected versus observed improvements in karate technique over four months of training. Expected improvements reflect the instructor's pedagogical goals and martial arts expertise. Observed improvements are quantified through biomechanical analysis of motion capture data*

Performance Indicator	Expected Improvement (Instructor Perspective)	Observed Improvement (Biomechanical Data)
Internal Consistency	Novices should develop more repeatable movement patterns with reduced variability within sessions	ACHIEVED: All novices showed increasing self-consistency, evidenced by rising correlation coefficients with their own final session patterns. Standard deviation bands narrowed over time.
Trajectory Patterns	General movement trajectories should match expert spatial patterns (forward, lateral, vertical directions)	ACHIEVED: All participants successfully emulated general trajectory patterns. Spatial path similarity was evident by the later sessions for most participants.
Velocity Development	Peak velocity magnitudes should increase as novices develop power generation capability	ACHIEVED: All novices demonstrated increased peak velocities. Parallel punch velocities increased from ~3-4 m/s to ~4.5-5 m/s. Front kick velocities increased similarly.
Two-Phase Velocity Pattern	Expert characteristic pattern (moderate approach → explosive impact) should emerge in novice movement	PARTIALLY ACHIEVED: Most novices did not develop clear two-phase patterns within 4 months. Only Novice 1 showed emergent pattern by final session. This proved more difficult than expected.
Peak Velocity Timing	Peak velocity timing should shift toward expert timing (final 70-90% of movement)	PARTIALLY ACHIEVED: Novices showed gradual shifts toward late-stage peaks, but most did not reach expert timing range consistently. This temporal aspect developed more slowly than velocity magnitude.
Task Space Accuracy	Final endpoint positions should converge toward consistent target locations	UNEXPECTED FINDING: Positional accuracy remained highly variable for both novices and expert. This revealed that exact positioning is less critical than velocity/acceleration patterns for technique effectiveness.
Technique Effectiveness (Overall Similarity)	Overall movement correlation with expert should increase progressively	MIXED RESULTS: Punching showed modest correlation improvements (limited to ~0.6-0.7 range). Kicking showed higher initial correlations (~0.7-0.8) suggesting front kicks are biomechanically easier to learn than punches.

Expert Biomechanical Signatures

Expert striking motion exhibited a characteristic two-phase velocity pattern across both punch and kick techniques: an initial moderate-velocity approach phase enables trajectory aiming and postural adjustment, followed by a sharp acceleration impact phase where maximum velocity occurs within 0.1 seconds of full extension. This pattern maximizes kinetic energy transfer at contact while minimizing energy expenditure during the approach. Peak forward velocity timing consistently occurs at 85% of motion for expert punches and 80% for kicks, concentrating force delivery at impact rather than throughout the movement. In contrast, novices display more uniform velocity profiles, suggesting they generate force continuously rather than explosively at the endpoint.

Expert motion demonstrates high internal consistency in trajectory patterns, with standard deviation bands remaining narrow across repeated trials. However, expert variability in execution time and certain endpoint positions equals or exceeds novice variability, indicating that expertise involves adaptive flexibility rather than rigid repetition. Expert performers prioritize consistent core biomechanical principles while allowing contextual adjustments in secondary metrics.

Expert task-space accuracy shows considerable variation in some directions. Lateral foot position during kicking exhibit wider distributions than expected. The lateral kick "error" reflects biomechanically sound center-of-mass shifting onto the supporting leg—a dynamic reference frame change that static coordinate analysis incorrectly classifies as positional error, highlighting the importance of analyzing motion relative to functional biomechanics rather than fixed coordinate systems.

Novice Biomechanical Development

Novice progression over four months demonstrated measurable improvements in trajectory pattern matching, velocity generation, and self-consistency, though expert-level characteristics remain undeveloped. Trajectory adaptation occurred in all novices, with later sessions showing convergence toward expert-like motion paths in both position and timing. Temporal-positional alignment improved, indicating novices learned not only where to move but when to move—critical for proper force generation. This adaptation was more pronounced in kicks than punches, as evidenced by higher correlation values with expert motion (Figure 5, Figure 7).

Peak velocity magnitudes increased across all novices, demonstrating improved power generation. However, the timing and sharpness of velocity spikes developed more slowly. Most novices did not achieve late-stage velocity peaks characteristic of expert motion, with only Novice 1 showing emergent two-phase patterns by the final session, suggesting that learning to maximize absolute velocity is more accessible than learning to precisely time explosive acceleration. Novice 1's prior muay thai experience may have facilitated this earlier development of expert-like velocity timing patterns. Acceleration improvements lagged substantially behind velocity improvements. While peak velocities increased relatively quickly (particularly in Novices 1, 2, and 4 during later sessions), the ability to generate sharp acceleration spikes at the correct moment developed slowly. Expert acceleration profiles show rapid onset and decay, whereas novice profiles remain broader and more gradual even after four months.

Internal consistency improved for all novices, evidenced by increasing correlation with their own final sessions (Figure 5, Figure 7). However, correlation with expert motion remained low throughout the study period, confirming that four months develops foundational skills but not expert-level biomechanical patterns.

Technique-Specific Biomechanical Differences

Front kicks proved to be biomechanically easier to master than parallel punches, with novices achieving higher correlation with expert kick motion compared to punch motion and faster self-consistency improvement. Kicks exhibit more discrete, sequential phases (chamber, extend, retract, return) that are biomechanically distinguishable, whereas punches require more continuous coordination of hand rotation, chambering, and force generation timing. Lower limb musculature is substantially larger and generates higher velocities (~6 m/s kicks vs ~5 m/s punches), making initial progress more apparent in velocity-based metrics.

However, kicks show larger movement variability across all participants. Expert kick trajectories demonstrate wider standard deviation bands than punch trajectories, particularly in forward and lateral directions, suggesting multiple valid execution paths exist for kicks, with effectiveness determined more by force generation and timing than precise positional accuracy. In contrast, punch trajectories show tighter clustering, suggesting more constrained optimal paths.

Lateral kick motion serves primarily aiming purposes, with peak velocity occurring mid-motion, while forward direction velocity peaks toward the endpoint for impact force. This directional differentiation, aiming in one direction, striking in another, requires more complex motor coordination than the predominantly forward punch motion.

Implications for Motor Learning

The four-month training period produced measurable biomechanical improvements but proved insufficient for developing expert-level characteristics. The sharp two-phase velocity pattern and late-stage acceleration spike fundamental to expert striking remained largely absent in novice performance, appearing only emergently in one participant. This timeline aligns with typical beginner progression, where foundational movement patterns are established before advancing to force optimization. The gap between novice and expert performance after four months emphasizes that expertise requires substantially longer practice to develop the neuromuscular coordination underlying expert biomechanical signatures.

Positional accuracy proved less critical than velocity and acceleration patterns for technique effectiveness. Novices showed wide variation in final endpoint positions yet still demonstrated improvement in other metrics, suggesting that motor learning prioritizes dynamic movement patterns and force generation over static positional precision, at least in early skill acquisition.

The finding that expert motion exhibited adaptive variability challenges traditional assumptions that expertise equals maximal consistency. Instead, experts appear to maintain consistent core biomechanical principles (velocity patterns, trajectory shapes) while flexibly adjusting secondary parameters (execution time, exact endpoints). This adaptive flexibility may itself be a characteristic of expertise, allowing skilled performers to adjust technique based on contextual demands while preserving functional effectiveness.

Limitations

The absence of impact targets during data collection may have reduced emphasis on positional accuracy and force generation compared to typical training environments. The small sample size (four novices, one expert) limits generalizability to broader populations, though the longitudinal design (32 sessions over 120 days) provides rich within-subject data. Biomechanical comparisons were descriptive rather than inferential due to limited sample size, and only correlational statistical testing were performed. In addition, only two techniques were examined; additional motions may reveal different biomechanical learning patterns.

5 Conclusion

This study characterized biomechanical signatures of expert karate technique and novice skill acquisition over four months. Expert motion exhibited two-phase velocity patterns (moderate approach, sharp impact acceleration) maximizing kinetic energy transfer while minimizing continuous effort. Peak velocity occurs at 85% of movement duration for punches and 80% for kicks, concentrating force delivery at the endpoint. Expert trajectories demonstrate high internal consistency in pattern shape but adaptive variability in execution time and certain endpoint positions, suggesting expertise involves flexible application of core biomechanical principles rather than rigid repetition.

Novice progression showed measurable improvements in trajectory pattern matching, peak velocity generation, and self-consistency. However, characteristic expert features, such as the sharp two-phase velocity profile and late-stage acceleration spike, remained undeveloped after four months, confirming that biomechanical expertise requires substantially longer practice. Kicks proved easier to master biomechanically than punches, likely due to more discrete sequential phases and larger musculature enabling visible progress in velocity-based metrics.

Importantly, biomechanical analysis reveals that positional accuracy is less critical than velocity and acceleration patterns for technique effectiveness. Dynamic movement patterns and force generation timing appear to drive skill development more than static endpoint precision, at least during early learning stages.

This work provides quantitative biomechanical characterization of karate skill acquisition, demonstrating that longitudinal motion analysis can identify objective performance indicators and track motor learning progression. These findings contribute to understanding how complex striking techniques develop and what biomechanical features distinguish expert from novice performance.

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Adherence to ethical standards

The experiments outlined in this manuscript have been reviewed by a University of Waterloo ethics committee and all participants provided written signed consent.

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