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Optimizing Swimming Performance: A Sensor-Based Analysis of Hand Position and Thrust Generation

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***Abstract*—The performance of a swimmer is hugely influenced by their hand position and thrust initiated by their hands, but due to the lack of scientific, data-driven, approaches to determining how to improve either of these two variables, coaching in India is often ineffective. In the current study, we presented a novel sensor system designed to investigate hand biomechanics and measure real-time thrust produced by the swimmers' hands. The systems comprised a glove, fitted with flex sensors, force-sensitive resistors, and an IMU housed within the glove, and a tethered loadcell system. Data was collected at one time-point in the pool, with swimmers performing four hand positions routinely used for front crawl: flat, cup, diagonal, and fingertip. Our preliminary results showed that the flat hand with mildly separated fingers had the most significant thrust produced, as well as being the most consistent, while cupped, and diagonally positioned hands were determined to be significantly less effective, and variable. Results from this study confirm previous hydrodynamic research, while advocating for the merit of biomechanical principles, and live feedback mechanisms for coaching. This study, by capturing motion and force data, synchronously, and with precision, presents a feasible and scalable form of intervention for performance improvement at an individual level, in the discipline of swimming for Indian participants, while it may also inform coaching decisions, assist in injury prevention, and establish superior swimming teams at a national level in future international competitions.**

***Keywords*—** *Swimming biomechanics, hand position, thrust generation, wearable sensor system, propulsion efficiency, real-time feedback, performance optimization, sports technology.*

I INTRODUCTION

According to the Worldometer, India is projected to become the most populous country on the globe by 2025, reaching a total of 1.46 billion people. More than 65% of this population will be aged 35 or less. With this demographic plus point, India is likely to become a sporting power. Despite these populations and potential bodies, India has been notoriously unsuccessful at the International Competition level related to swimming. In the last 50 years, India has won three medals in swimming in the Asian Games and has never won an Olympic medal in swimming. Traditional coaching has utilized a focus on amount of increase training, speed and intensity of the sessions, ignoring where knowledge of sports science will assist the alteration of technique and performance. To counter this issue, the study proposed will design an innovative device that will look to investigate swimming techniques while also looking to improve the techniques in situ. The device would contain several high-precision sensors to investigate hand position, finger angle, and thrust produced and combine it with Coaching Feedback which will poorer understanding to the participants as they perform the swimming. Utilising a data driven training method is a contemporary trend in sport and exercise science to formulate a better athlete's performance.

The importance of this investigation is highlighted by the demographic reality of India given the contingent of young and developing athletes. The student wishes to discuss opportunities and constraints in coaching practices associated with swimming, and employ sounds, evidential bases or rationale to capitalise on this opportunity in an effort to raise India's competitiveness in swimming at a global level.

More broadly, recent competitions such as the Asian Games have shown areas of unrealized potential within Indian swimming. For example, at the 2023 Asian Games in Hangzhou, Indian swimmers broke six national swimming records, showing they are making legitimate advancements, despite their inability to win medals (olympics.com). This provides evidence supporting that in the right spaces and in the right circumstances with additional supports, Indian swimmers can obtain greater success in competing against other countries.

To do this, this study aims to present a transition from conventional training to evidence-informed and scientific practices and strategies that will assist swimmers in modifying and/or uniquely changing their energy in performance contexts and environments. By focusing on encouraging appropriate hand positions to help develop and improve mechanics, while minimizing wasted energy will likely support the development of a competent and efficient swimming training program for Indian swimmers.

II Literature Review

The biomechanics of swimming has been extensively investigated, with early reviews describing how lift, drag, and hand–forearm geometry combine to create propulsion efficiency **[1]. Koga et al.** subsequently provided experimental data that connected hand kinematics, surface pressure distribution, and instantaneous propulsive force in sprint front crawl swimming, finding that local pressure differences on the palm highly correlated with thrust production [2]. Given this information, more recent hydrodynamic syntheses compared computational modeling, tow-tank, and in-pool studies that explored the influence of finger position, hand angle of attack, and arm sweep on propulsion [3].

Inference of active drag as measured under crawl arm strokes has first been conducted by **Hollander et al.**, who pointed to the issue of measuring difficulty as well as the significant influence of stroke mechanics on drag forces [4]. Flow-tank trials later reported that hand position had a large influence on efficiency, though dynamic effects generally superseded static drag differences [5]. Likewise, van Houwelingen et al. reported a small amount of finger spread could deliver propulsive drag greater than drag by a measurable amount, confirming prior computational works analysis [6].

To examine hand forces applied, **Gourgoulis et al.** had Paddles used and thought applied propelling efficiency could be inferred, demonstrating that paddles provided more force but altered the stroke mechanics [7]. In a different approach, **Psycharakis et al.** focused on tethered swimming devices, assessing reliability, stating a systematic error that calibration procedures should address before use [8]. Other broader methodological critiques further questioned accuracy in force estimation methods stating new propulsive force methods miss represent swimmer to fluid shove when models are not validated [9]. Hydrodynamic syntheses have contrasted methods from computation, tow-tanks, and in pool methods in part to illustrate how finger separation, hand angle of attack, and horseshoe arm structure could best overall propulsion [3].

Asymmetries in propulsion have been reported in tethered swimming, with dos **Santos et al.** noting substantial bilateral propulsive force imbalances during front crawl [10]. Studies by **Morouço et al.** extended these findings by showing tethered testing force measures are strongly correlated with sprint performance. They could represent an individual assessment tool for contributions to swimming short distance events [11]. Reiterated discussion of asymmetry emphasizes the necessity of bilateral force monitoring to mitigate risk of performance decline or injury [12]. Most recently, **Papoti et al.** applied tethered protocols for resistance training with young swimmers demonstrating their value for determining loads and monitoring adaptation and development [13].

Van den Berg et al. showed that a small amount of finger splay increases drag which causes greater thrust through the stroke [14]. Sidelnik found a 10° spread created greater stroke forces relative to fingers together which improves propulsive efficiency [15]. Collectively, this evidence suggests small changes in finger position can greatly influence water displacement and thrust. These studies indicate that optimizing both hand positioning and hand splay are important to improve swimming stroke effectiveness.

While the prior literature has added to the knowledge of hand posture and finger spacing and tethered force measurement, most studies have evaluated these variables in isolation, often in over-simplified contexts. Little effort has been made to evaluate finger level measurement (with flex and force sensors), hand orientation (with IMUs), and direct measurement of tethered thrust in natural swimming environments. In addition, the scientific community has paid limited attention to identify the catch and propulsion phases of the stroke in association with each modalities synchronized multimodal assessments. The method proposed herein, which combines sensorized gloves, IMUs, and load cell systems, addresses this gap, by providing an integrated in-pool measurement system that can capture fine-grained biomechanical detail, that will provide directly constructed measures for individualized performance measurement and optimization.

III METHODOLOGY

1. *Experimental Design*

In this research, a dual-sensor system was used to study hand biomechanics in relation to thrust in swimming. The system consisted of two subsystems; (i) a wearable glove equipped with sensors to collect data on finger posture, fingertip pressure and hand orientation, and (ii) a thrust measurement system which used a tether to measure net propulsive force. Each system was connected wirelessly by ESP32 microcontrollers to allow for the collection of kinematic and kinetic data simultaneously.

Each participant performed four hand postures across repeated swimming trials:

1) Hand flat and perpendicular to the water with fingers slightly spaced.
2) Hand flat with fingers together.
3) Cupped hand during pull.
4) Hand positioned diagonally, producing lateral rather than forward thrust.

Trials were conducted under controlled pool conditions to ensure consistency in swimmer movement and data capture.

2. *Wearable Glove System*

The glove was made to capture dynamic hand parameters during the catch and propel phases of the stroke.

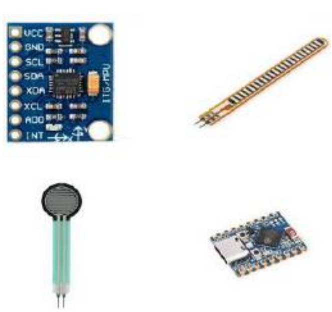

Fig. 1: Electronics Components on the glove

- **Flex Sensors (five units):** Attached to each finger to record joint angles, while noting changes in cupping or spreading of the fingers.
- **Force-Sensitive Resistors (five units):** Attached to finger tips to measure pressure distribution of fingertip pressure for determining which fingers contributed the most to propelling.
- **MPU6050 IMU:** Fixed to the back side of the hand to assess its orientation (pitch, roll, yaw) for thrust vectoring insights.
- **ESP32-S3 Mini:** Collects sensor signals, preprocesses the data, and transmitted it via Wi-Fi to the main computer.

3. *Thrust Measurement System*

To measure propulsion, a swimmer was tethered via a waist belt connected to a poolside anchor through a load-cell assembly.

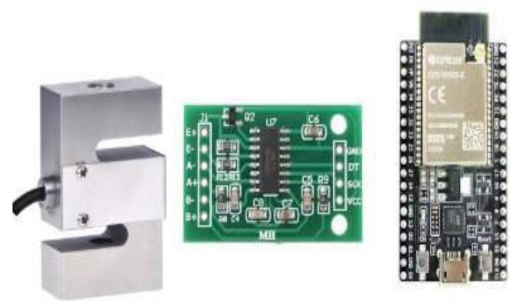

Fig. 2: Load cell electronics components

- **Z-Beam Load Cell:** Represents the axial thrust generated by the swimmer during the propelling phase, validated.
- **HX711 Signal Amplifier:** Converted low voltage strain gauge outputs into digital values.
- **ESP32 DevKit:** Taped into HX711 to collect the force data, and wirelessly transferred it to the computer for synchronization with glove data.

4. *Data Transmission and Synchronization*

The ESP32 module (S3 Mini on glove, DevKit for load cell) are connected to the same universal WiFi to continuously transmit data packets containing timestamps, sensor IDs, and raw values over TCP/IP to a specific computer. A logging interface in Python collected all the incoming data streams in real-time and synchronized the data streams to create data sets for each trial.

Fig. 3: Actual Testing Setup

5. *Data Analysis*

The collected data were categorized by swimming posture and analyzed for:

- **Thrust Force:** Peak and average propulsive force values from the load-cell system.
- **Hand Orientation:** IMU-derived pitch, roll, and yaw values correlated with thrust generation.
- **Finger Posture and Pressure Distribution:** Flex and FSR sensor data mapped against force outcomes.

Multivariate analyses would later be performed to understand which hand posture produced the most propulsion. The combined results would then be used to provide swimmer specific recommendations for optimization of technique.

IV RESULTS

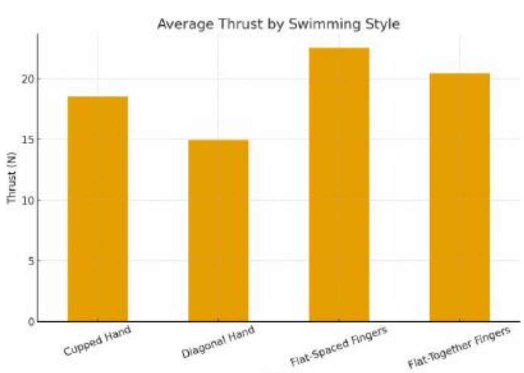

Fig. 4: Average thrust by swimming style.

Figure 4 shows The bar graph illustrates the mean thrust produced across all trials for each of the hand configurations and shows that the Flat-Spaced Fingers configuration provided the highest mean thrust overall, while the Diagonal Hand configuration produced the least thrust of all configurations.

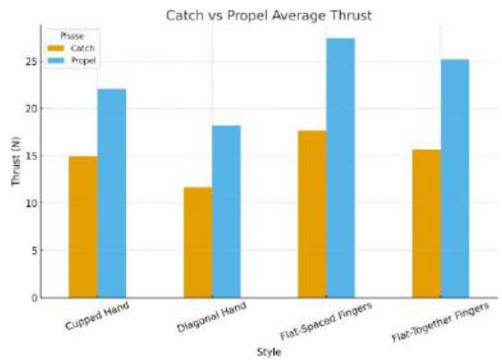

Fig. 5: Catch vs. propel phase comparison.

Figure 5 shows comparison between catch and propel phase. There are also mean thrust levels that pertain to each phase. Overall, thrust levels in the propulsion phase across all conditions were considerably higher than thrust levels in the catch phase. A noteworthy finding is that the Flat-Spaced Fingers configuration, which produced the highest thrust levels in the propulsion phase across all configurations, surpassed the others in propulsion.

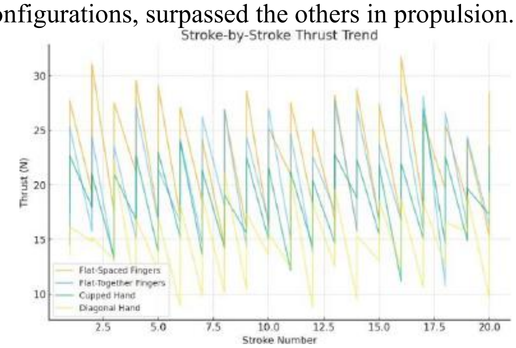

Fig. 6: Stroke-by-stroke thrust trends.

The figure 3 illustrates the stroke-by-stroke thrust produced by different hand positions over 20 strokes. It shows that the flat-spaced fingers generate the highest thrust peaks, while the diagonal hand consistently produces the lowest. Both the flat-together fingers and cupped hand configurations exhibit intermediate thrust values with similar trends. Overall, the graph highlights how hand posture significantly affects the magnitude and consistency of thrust during each stroke.

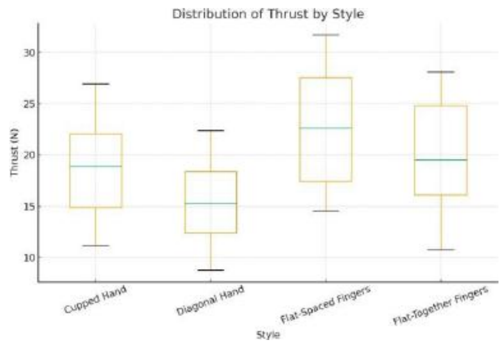

Fig. 7: Distribution of thrust values by style.

Boxplots highlight the variability and spread of thrust data for each configuration. The Flat-Spaced Fingers posture exhibits a higher median with moderate variance, while the Diagonal Hand style shows the lowest and most inconsistent thrust values, suggesting inefficiency in force application.

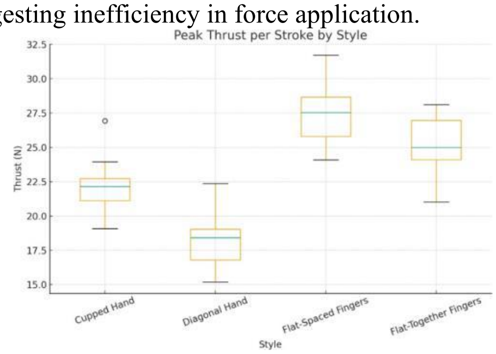

Fig. 8: Peak thrust per stroke by style.

The boxplots of maximum thrust values per stroke highlight the relative capabilities for each posture to thrust at an optimal peak output. The FlatSpaced Fingers style provides the highest peak values, whereas the Cupped and Diagonal postures are less impressive.

TABLE I: Quantitative Summary

Style	Avg Catch (N)	Avg Propel (N)
Cupped Hand	14.94	22.10
Diagonal Hand	11.71	18.16
Flat-Spaced Fingers	17.65	27.48
Flat-Together Fingers	15.66	25.22

The table 1 displays cantered average forces during catch and propulsion phases with different hand positions. "Flat Spaced Fingers" had the highest forces indicating maximal propulsion while "Diagonal Hand" had the lowest. In between these two extremes, "Cupped Hand" and "Flat Together Fingers" showed average values where one the hand position had more stability and the other had more propulsion. Each hand position produced variable values respectively indicating that each had an effect regarding efficiency in the swimming stroke.

V DISCUSSION

The evaluated conditions resulted in clear differences in propulsion efficiency over the four hand positions. The flat hand position with slightly spaced fingers produced the most thrust (27–28 N), with smoother and more consistent catch–propulsion curves compared to conditions with together fingers. Overall, this configuration produced the greatest effective surface area while also minimizing loose water, which is consistent with previous hydrodynamic findings reported in the literature which report 8% greater propulsion for fingers spaced apart [Lecrivain et al., 2008; Minetti et al., 2009]. The FSR data confirmed that the index finger and middle finger are especially responsible for forwards thrust during swimming.

The tight fingers position led to a reduction in the peak thrust(f 23–24 N) production despite being stable and repeatable. Similarly, the force profiles were relatively stable but did not have the same amplitude that the spaced fingers condition provided as the effective area was less represented with fingers tightly together. The pressure distribution was principally centered on the palm of distal or inner fingers, yielding effective working efficiency but less overall propulsion, which could still be advantages for distance swimmers.

The cupped-hand position yielded lower performance (18–20 N) with irregular force curves and different fingertip pressures. Although the posture facilitated the idea of 'scooping' the water, the cupped hand reduces effective surface area and increases turbulence and wasted effort. This posture should not be used while teaching, especially with younger swimmers.

The diagonal hand position had the lowest thrust force recorded (12-15 N). IMU and load cell data confirmed yawed force vectors that redirected flow laterally, resulting in inefficient catch and propulsion. In addition to inefficiency, straw the position could cause strain in the swimmer's shoulders and thus future performance. If attempting to correct their diagonal position, drills such as sculling should be emphasized.

Overall, spaced fingers were the most effective for propulsion, and closed fingers provided an energy efficient alternative, while cupped or diagonal palm positions should be discouraged. The glove–load cell system demonstrated a true measurement of these biomechanical differences and consequently demonstrates value in performance monitoring and individualized training feedback.

VI Conclusions

The results of this study reinforce the importance of hand posture on the propulsion created through swimming. While hand variations were assessed, the flat hand with a little separation between the fingers was identified as the best method to generate propulsion (thrust) and maintain the stability of the stroke. In contrast, the cupped hands and diagonal hand orientation produced decreased efficiency, increased turbulence, and decreased propulsive forces in the lateral plane of motion. The combination of flex sensors, FSRs, IMU data, and a mounted tethered load cell collected prompt multi-system synchronized collection of quantitative data of each global catch and propulsion stroke position. This methodology documented inefficient positions of the body or limbs during the stroke mechanics and supported evidence

in detecting correcting hand positions early in the training process. Overall, the study indicates biomechanical optimization of a swimmer's stroke, and the sustained use of multisensory feedback, can increase swimmer performance and minimize wasted energy and injury in the use of incorrect stroke mechanics.

Future research should aim expand trials to larger swimmer populations with varying abilities to generalize results. The system could be improved to provide real-time wireless feedback to allow swimmers and coaches real-time corrective cues during practice. Future integration with machine learning models could create the potential for individualized optimization of stroke mechanics ultimately creating a potentially practical, wearable coaching tool for competitive and training swimmers.

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