ADAPTIVE SOLUTIONS: ASSISTIVE DEVICE FOR OPTIMAL STROKE PROFILE FOR MOBILITY-IMPAIRED INDIVIDUALS

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ABSTRACT

This study addresses the limitations of current adaptive sports equipment, specifically focusing on adaptive kayak mounts for individuals with mobility impairments. In the United States, where 12.1% of the population faces significant mobility challenges, adaptive sports play a crucial role in enhancing physical well-being and reducing social isolation. However, existing devices often restrict natural movement patterns and fail to

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meet user-specific needs, impacting overall user experience. This research introduces a novel approach using motion capture technology and advanced optimization techniques to redesign adaptive kayak mounts. Central to this study is the development of a four-bar linkage mechanism designed to replicate the natural kayak stroke profile. Motion capture data from a series of trials informed the design process, ensuring alignment with the ideal stroke pattern across various user skill levels. The study evaluates the effectiveness of two distinct designs—the elite and leisure linkage models—through Root Mean Squared Error (RMSE) analysis, demonstrating their capability to accurately replicate desired kayak stroke motions while prioritizing user comfort. Results indicate that the elite linkage design achieves high accuracy (RMSE = 22.0 mm) in replicating the standard kayak stroke, enhancing performance for competitive users. Conversely, the leisure linkage design, tailored for recreational use with reduced input requirements, maintains a balance between functionality and comfort, broadening accessibility in recreational sports. By addressing critical gaps in current adaptive technology, this research contributes to improving inclusivity and user satisfaction in adaptive kayaking, thereby enriching the recreational experiences of individuals with mobility impairments.

INTRODUCTION

In the United States, 12.1% of individuals live with a significant mobility disability impacting their day-to-day lives [1]. Furthermore, 71% of those with mobility impairments report experiencing emotional stress and social isolation. Engagement in adaptive sports has been shown to enhance physical well-being and improve quality of life by fostering meaningful social connections [2]. Consequently, adaptive sports have seen substantial growth due to their ability to break down social barriers, empower individuals, and enhance overall quality of life for those with mobility impairments. These initiatives promote inclusivity and encourage participation in both recreational and competitive sports, enabling individuals to partake in community activities despite their physical limitations

A critical component of adaptive sports participation is the availability and efficacy of adaptive devices. These devices are essential for enabling individuals with mobility impairments to fully engage in sports and recreational activities [3]. However, existing equipment often fails to meet the specific needs of users, particularly in facilitating natural and effective movement patterns. Many current devices lack sufficient adjustability and adaptability, forcing users to conform to the device rather than the device accommodating the user's requirements. This can lead to inefficient movements, increased physical strain, and a diminished overall experience [3].

In the context of adaptive kayaking, several devices are used to assist individuals with mobility impairments. Among these, adaptive paddle holders and stabilizing mechanisms are the most prevalent. The Angle Oar Gamut Paddle Holder, for instance, is a widely used device designed to stabilize the paddle using a ball-and-socket joint as depicted in "Fig. 1". While this design offers stability, it restricts the user's movement to rotational degrees of freedom (DOF), limiting the ability to perform a natural paddle stroke. This restriction can make it challenging for users to keep pace with kayaking demands, as their range of motion (ROM) is constrained. Users of the Gamut Paddle Holder often find that it does not adequately mimic the complex, multi-phase motion of a standard kayak stroke, thus limiting the overall kayaking experience.

Another commonly used adaptive device is the Pivot Paddle, which offers a pivoting mechanism to aid in paddle movement. This device can assist users with limited upper body strength by providing a pivot point, thus reducing the effort required to move the paddle through the water. However, similar to the Gamut Paddle Holder, the Pivot Paddle's design does not fully replicate the natural kayak stroke and often results in a less efficient paddling motion. This inefficiency can lead to increased fatigue and reduced enjoyment for the user.

The Adapt2It Kayak Paddle Holder is another example that provides support by attaching to the kayak and holding the paddle in place. This device helps stabilize the paddle, making it easier for users to manage their strokes. However, it also suffers from limitations in ROM and adaptability, preventing users from achieving a fluid and effective paddling motion.

Despite the advancements in adaptive sports equipment, existing devices often fail to fully meet user needs in terms of natural movement and adaptability. This study builds upon previous research by proposing a novel four-bar linkage design that aims to bridge these gaps, offering a more ergonomic and effective solution for adaptive kayaking.

To address these limitations, this study proposes the redesign of the adaptive kayak mount to better align the ROM with a natural forward stroke for kayakers. Leveraging motion capture data, a four-bar linkage system is designed to replicate the standard stroke profile (SSP) of a kayak paddle. This design aims to provide an ergonomic and efficient solution, enhancing the kayaking experience for individuals with mobility impairments. By aligning the ROM with the ideal stroke pattern, the new mount is intended to facilitate a more natural and effective paddling motion, reducing physical strain and improving overall user experience.

This innovative approach addresses current market gaps by offering a device that adapts to the user's needs, promoting inclusivity and encouraging greater participation in adaptive sports. The new adaptive kayak mount not only enhances the physical performance of the user but also contributes to their psychological well-being by enabling them to engage more fully in a rewarding and socially inclusive activity.

MATERIALS AND METHODS

In the study by Walck et al. (2023), motion capture technology was employed to collect detailed data over the course of 15 trials, focusing on a 21-year-old male participant performing a standard kayak paddle forward stroke [4]. The resulting motion profile exhibited maximum dimensions of 768 mm along the mediolateral axis (y), 473 mm along the superior-inferior axis (z), and 502 mm along the anterior-posterior axis (x), characterizing a semi-ellipsoidal motion pattern. To facilitate subsequent analysis, the data was extrapolated to establish the theoretical center point of the kayak paddle by calculating the midpoint of the two paddle endpoints for each frame, resulting in a single motion profile. This standard stroke profile (SSP), illustrated in “Figs 2-3”, serves as a guiding principle in the redesign, ensuring that the adaptive kayak mount aligns with the ideal stroke pattern and enhances user experience. The SSP defines the range of motion (ROM) in the sagittal, frontal, and transverse planes of the redesigned paddle mount center, spanning 420 mm along the mediolateral axis (y), 198 mm along the superior-inferior axis (z), and 168 mm along the anterior-posterior axis (x).

By utilizing motion capture technology and advanced optimization techniques, this research provides a detailed analysis of how the proposed adaptive kayak mount enhances the replication of natural kayak strokes compared to existing devices. The discussion highlights the significance of these findings in improving user experience and performance in adaptive kayaking.

4-Bar Linkage Design

The redesign utilizes a four-bar linkage mechanism to replicate the path of a forward kayak stroke. A four-bar linkage, the simplest movable closed-chain linkage, can map a profile based on the dimensions of its constituent links [5]. This linkage consists of a crank, rocker, coupler, and two grounded base points, modeled to the sagittal plane profile of the paddle's center point. The parameter dimensions, as shown in “Fig. 5”, include the triangular coupler lengths $\boldsymbol{\gamma}$, $\boldsymbol{\beta}$, and $\boldsymbol{\alpha}$, with the triangular coupler link points A, B, and C. The crank and rocker lengths are represented by k and Γ, respectively, with ground points of the crank and rocker designated as P and R. he vertical distance between the ground points is given by v, and the horizontal distance by u. The angle θ measures the crank's rotation with the horizontal axis, which rotates through a full 360 degrees. The angle ϕ represents the oscillating angle the rocker link makes with the horizontal axis.

Four-bar linkages are classified into Grashof-type and non-Grashof-type linkages [6]. Grashof linkages satisfy the Grashof condition, which states that if the sum of the shortest and longest link is less than or equal to the sum of the remaining two links, then the shortest link can rotate fully with respect to a neighboring link. The crank-rocker configuration of a Grashof-type four-bar linkage is governed by the following equations [6].

$$A_x = P_X + k\cos(\theta) \quad (1)$$

$$A_y = P_y + k\cos(\theta) \quad (2)$$

$$\alpha^2 = (A_x - B_x)^2 + \left(A_y - B_y\right)^2 \quad (3)$$

$$\beta^2 = (A_x - C_x)^2 + \left(A_y - C_y\right)^2 \quad (4)$$

$$\gamma^2 = (B_x - C_x)^2 + \left(B_y - C_y\right)^2 \quad (5)$$

$$B_x = R_X + \Gamma\cos(\phi) \quad (6)$$

$$B_y = R_y + \Gamma\sin(\phi) \quad (7)$$

$$k^2 = (P_x - A_x)^2 + \left(P_y - A_y\right)^2 \quad (8)$$

$$\Gamma^2 = (R_x - B_x)^2 + \left(R_y - B_y\right)^2 \quad (9)$$

$$\phi^2 = \frac{\theta - \tan^{-1}\left(\alpha^2 + \beta^2 + \gamma^2\right)}{2\alpha\beta} \quad (10)$$

Each link length was capped at 31.3 inches (0.795 meters) to remain below the minimum sitting eye height, as per the "Ergonomics and Design" reference guide by Openshaw & Taylor (2006) [7]. The linkage profile assumes a crank-rocker profile, given an input angle from the crank and an oscillatory angle of the rocker defined by the following equations 11 and 12 where the crank angle θ rotated through a full $360°$ and the rocker angle ϕ between a min and max value.

$$\theta \in [0, 360°] \quad (11)$$

$$\phi \in [\phi_{min,} \phi_{max}] \quad (12)$$

The Optimization Toolbox in MATLAB v2023 was used to optimize the linkage design, employing a multi-objective optimization algorithm to minimize the maximum difference between two data sets [8]. This method addresses a set of nonlinear functions that define a system linkage, seen in equations 1-10, to map the output of the linkage couple path $F_i(x)$ to a goal-set F'_i, in this case, the SSP in the sagittal plane. The minimizing method iteratively determines the loci of a minimum relative difference between two data sets. The datasets compared consisted of a 22-point dataset of the sagittal plane SSP to the output 22-point dataset profile of the linkage mechanism at point “C” seen in “Fig. 4”. The linkage lengths were determined using the bounded constraints given in relations 11 and 12, the maximum component dimension of 31.3 inches, and an objective function of the linkage equations 1-10 defining the $F_i(x)$ dataset path to the goal path.

Feedback from users (n=30) associated with the Oceans of Hope Foundation highlighted the need for a more relaxed range of motion (ROM) better suited to leisure kayakers. In response, the input crank length was reduced by 60% compared to the elite design (“Fig”. 5), aiming to enhance comfort and usability during leisurely kayaking experiences. This adjustment resulted in a maximum bounded crank length of 3.87 cm. Concurrently, efforts were made to maintain consistency in the width parameter u of the linkage mechanism, ensuring uniformity in attachment design and transition across both elite and leisure designs. Detailed parameters for the leisure linkage design are provided in Table 2, distinguishing it from the original elite linkage design developed from the full SSP (Figure 6).

RESULTS AND DISCUSSION

The adaptive kayak mount redesign project focused on accommodating the diverse needs of users, resulting in the development of the leisure linkage design derived from the elite linkage. Optimized linkage parameters based on the SSP and employing a minimizing maximum method are detailed in Table 1. “Fig.” 6 illustrates the full sagittal plane SSP for both elite and leisure linkages, providing a comparative analysis against the SSP derived from the State-of-the-Art profile, which assumes cyclic elevation and exit angles of 133.17 and 20 degrees, respectively, typical of kayak paddle strokes [9].

A Root Mean Squared Error (RMSE) analysis was employed to assess the accuracy of the linkage designs in replicating the desired kayak stroke motion, utilizing a 22-point dataset obtained through motion capture (y_i) compared to the SSP trajectory ($\bar{y}_i$) [10]. This statistical measure quantifies the average magnitude of discrepancies between predicted and observed values, where a lower RMSE value indicates closer alignment with the SSP.

$$RMSE = \sqrt{\frac{\sum(y_i - \bar{y}_i)^2}{n}} \qquad (13)$$

Table 3 presents the RMSE values for the State-of-the-Art, elite, and leisure designs. The State-of-the-Art paddle holder exhibited a high RMSE value, indicating significant deviations from the ideal SSP and suggesting room for improvement in motion replication. In contrast, the elite linkage design, which served as the basis for the leisure design, demonstrated a low RMSE, highlighting its capability to accurately replicate the desired kayak stroke motion as defined by the SSP. The leisure linkage design, while prioritizing user comfort with adjustments such as a reduced input crank length, showed a slightly higher RMSE compared to the elite design, indicating compromises in motion accuracy.

Addressing Gaps in Current Devices

Current adaptive kayak devices often struggle to fully meet the diverse needs of users, particularly in providing a balance between performance and user comfort across different skill levels and preferences. The development of the leisure linkage design from the elite design in this study addresses these gaps by optimizing for user comfort without sacrificing significant motion accuracy. By leveraging advanced optimization techniques and tailored adjustments, this study contributes to enhancing the inclusivity and effectiveness of adaptive kayak mounts, thereby fostering greater accessibility and enjoyment for individuals with mobility impairments in recreational and competitive kayaking.

CONCLUSION

This study lays the foundation for future research directions in adaptive sports technology, suggesting potential enhancements and innovations to further improve the inclusivity and effectiveness of adaptive kayak mounts. Furthermore, this study underscores the pivotal role of adaptive technologies in enriching recreational experiences for individuals with mobility impairments. The primary objective was to overcome the constraints of current devices and improve overall usability for diverse user groups. By utilizing motion capture data and implementing a four-bar linkage mechanism, we successfully developed two distinct designs: the elite and leisure linkage designs, tailored to meet varying user needs.

The elite linkage design, meticulously optimized to replicate the standard kayak stroke profile with exceptional accuracy (RMSE = 22.0 mm), represents a significant advancement in adaptive technology. This precision ensures that elite users experience optimal performance and efficiency during kayaking, thereby enhancing their overall sporting experience.

Conversely, the leisure linkage design, derived from the elite model, prioritizes user comfort and ease of operation while maintaining a balance between functionality and reduced load. Despite a marginally higher RMSE of 79.7 mm, this design offers recreational kayakers a smoother and more relaxed kayaking experience, thereby broadening accessibility and inclusivity in recreational sports.

This research highlights the feasibility and importance of advancing adaptive devices to accommodate diverse user requirements in sports and recreational activities. By addressing the distinct needs of users with mobility impairments, this study contributes significantly to fostering a more inclusive environment in sports, ultimately enhancing the quality of life and participation opportunities for individuals facing mobility challenges. Future research should continue to refine these designs and explore additional innovations to further improve adaptive technologies in recreational sports.

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NOMENCLATURE

ERAU	Embry-Riddle Aeronautical University
OOHF	Ocean of Hope Foundation
ROM	Range of Motion
DOF	Degrees of Freedom
FS	Forward Stroke
SSP	Standard Stroke Profile

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FIG. 1: State-of-the-Art Gamut paddle holder by Angle Oar Inc.

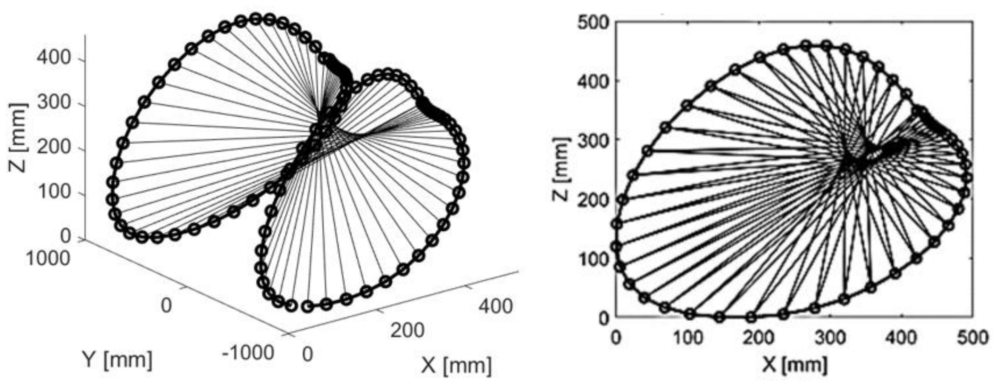

Fig. 2: Standard stroke profile (left)and sagittal plane standard stroke profile (right)

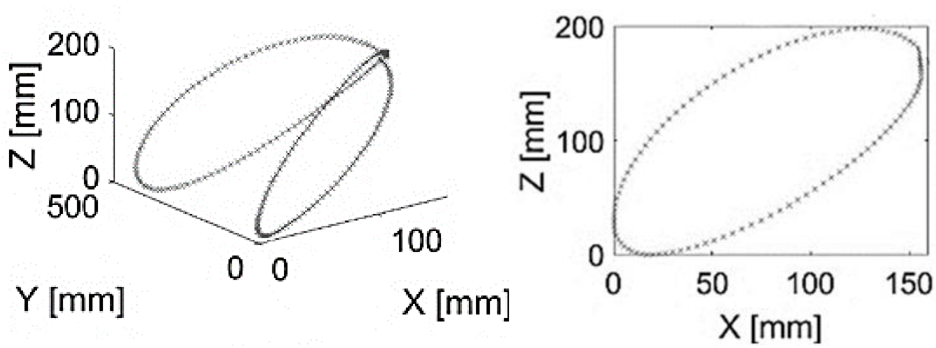

Fig. 3: Centrepoint standard stroke profile (left) and sagittal plane centrepoint standard stroke profile (right)

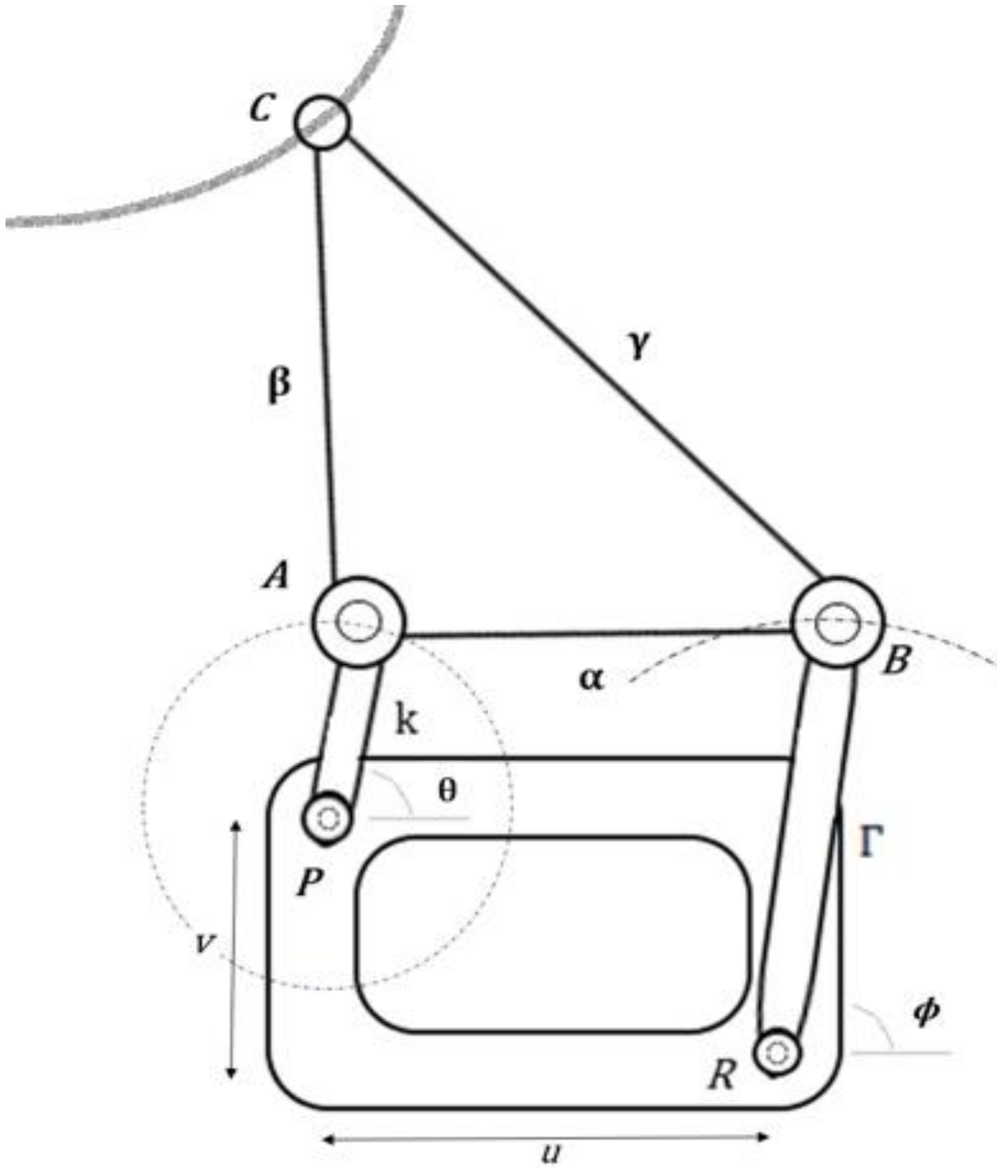

Fig. 4: 4-bar linkage model

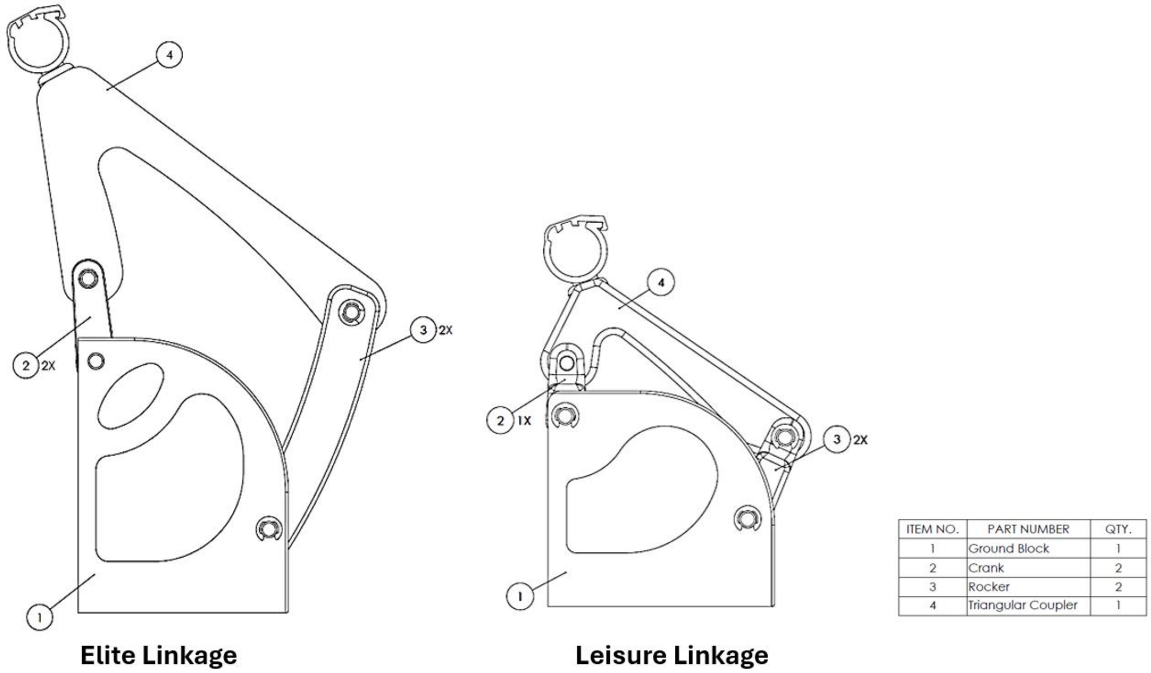

Fig. 5: Models of the elite linkage (left) and leisure linkage (right)

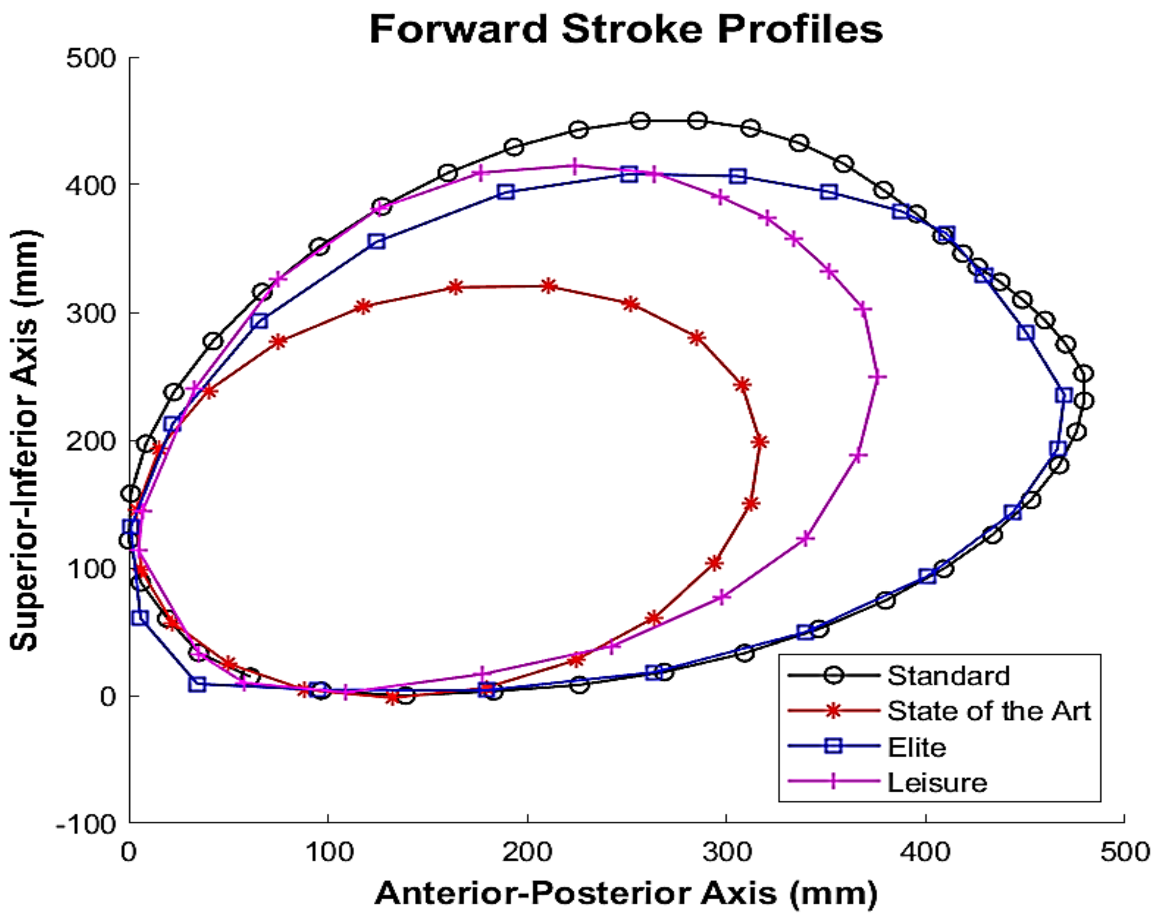

Fig. 6: Forward stroke profiles of the SSP, state-of-the-art, elite, and leisure paths

TABLE 1: Elite linkage dimensions

Triangular Coupler		Links		Ground Points	
α	20.73	Γ	18.09	u	13.51
β	20.73	k	6.45	v	12.22
γ	34.19				

[α]*All measurements in [cm]*

TABLE 2: Leisure linkage dimensions

Triangular Coupler		Links		Ground Points	
α	17.20	Γ	18.09	u	13.51
β	6.89	k	3.87	v	7.78
γ	19.89				

$^{\alpha}$*All measurements in [cm]*

TABLE 3: RMSE of state-of-the-art, elite, and leisure paths to the SSP

Path Profile	RMSE [mm]
State of the Art	272.7
Elite Evans Linkage	22.0
Leisure Evans Linkage	79.7