2023 20th International Conference on Ubiquitous Robots (UR)
June 25-28, 2023. Hawaii Convention Center, Honolulu, Hawaii

A Transradial Prosthesis with a High-Functional Wrist for Various Daily Living Task

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***Abstract*— About 41,000 upper limb amputees in the US often face challenges in performing activities of daily living (ADL) that require the assistance of prostheses. Recently, various upper limb prosthetic hands are suggested to have higher complexity and degree of freedom, while the prosthetic wrist remains passive or has only one active degree of freedom. Such designs can lead to higher compensatory unnatural motion, which can lead to pain and discomfort of the residual limb. Having a higher degree of freedom wrist can significantly reduce unnecessary compensatory motion and overuse of the intact side of the limb as well. The UBArm is designed for a three-degree of freedom wrist and one-degree of freedom hand. It can actuate all three wrist motions including pronation/supination, radial/ulnar deviation, and flexion/extension. We envision highly functional wrist of UBArm with lighter weight can provide better support to ADLs of amputees and reduce unnatural motion to maximize comfort.**

I. INTRODUCTION

The loss of a limb can alter the livelihood of an individual that can cause challenges faced for them on a daily basis. Up to 41,000 upper limb amputees in the US face hardships when performing activities of daily living (ADL), while using prostheses [1]. Therefore, it can be crucial towards the livelihood of an amputee to perform basic tasks using the assistance of prostheses [2].

Transradial amputation indicates amputation anywhere below the elbow up until the wrist of the forearm. This prostheses can include some or most degrees-of-freedom (DoF) that a human forearm has. The human forearm consists of a hand that has around 22 different DoF actuated by 34 different muscle [3]. In additon, there are three active wrist rotations in a human forearm [3]. These motions or DoF are the Radial and Ulnar Deviation (RUD); Pronation and Supination (PS); Flexion and Extension (FE). Wrist motions are considerably more crucial towards an ADL arm-based tasks in comparison to the hand [4]. It is quite challenging to fit the necessary actuators, controllers, and electronics within a small forearm size.

In order to address these issues, researcher explored what would be the most optimal design of transradial prostheses. Some studies showed that under-actuated and decreased DoFs are fully capable of performing ADL tasks ([5], [6]). Other studies suggest that an optimal design of a transradial prosthesis depends on the type of ADL tasks it designed for. Most arm based ADL tasks focus less on the dexterity of the hand and more towards the functionality of the wrist. Thus, it was concluded that a 3 DoF wrist and 1 DoF hand can provide as much or equivalent results as a high DoF hand and 1 Dof wrist [4].

There are numerous designs, development, and research in the field of powered prostheses for the upper limb amputation. Many of these designs focus on the implementation of a highly sophisticated multi-degree of freedom hand, while maintaining only one degree of freedom wrist. Some prostheses like LUCS Haptic Hand has a 1 DoF wrist with a 6 DoF hand use multiple RC servo motors as the actuators [5]. The DARPA Luke Arm (Transradial version) uses various of sensors with a 3 DoF wrist and up to 15 DoF in the hand [5]. It uses DC motors and is relatively light weight in comparison to the number of DoF ([7], [6]). The Smart Hand has up to 16 DoF, but with only 4 motors to actuate all the DoF [8]. The Vanderbilt multi-grasp (VMG) hand is a 9 DoF hand with 4 motors actuating the hand [9]. There are two DC motors dedicated to the thumb actuation, while the remaining two are used towards the rest of the four fingers. Although the Smart Hand and VMG hand may be under-actuated, it still requires multiple actuators to control the prosthetic hand. For multi DOF wrists, the University of Moratuwa (UOM) proposed by Bandara features a 3 DoF wrist and a 7 DoF hand [10]. The three DoF uses a system of linear actuators, ball joints, and universal joints in order to actuated all the wrist motions. The Bajaj wrist uses a spherical joint, motors, and linear actuators to actuated all 3 DoF of the Wrist [11].

UBArm is a transradial prosthetic that was designed and built to implement a 3 DoF wrist and 1 DoF Hand. This configuration offers the best in terms of reduction in complexity and compensatory motions, while being able to perform ADL tasks similar to the current available prosthetic [12]. The UBArm is also designed to minimize weight and size in comparison to most transradial prostheses. It features a 4-bar link gripper actuated with a single servo motor. One servo motor for the RUD mechanism and Maxon Motors for the PS and FE motions. The UBArm is also designed to be light weight, compact, and controllable using wearable electronics.

*This research was supported by Disability and Rehabilitation Engineering (DARE) Program under National Science Foundation Award (CBET-2221979) and partially suppported by GIST Start-up fund (123004).

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2023 20th International Conference on Ubiquitous Robots (UR) | 979-8-3503-3517-0/23/$31.00 ©2023 IEEE | DOI: 10.1109/UR57808.2023.10202316

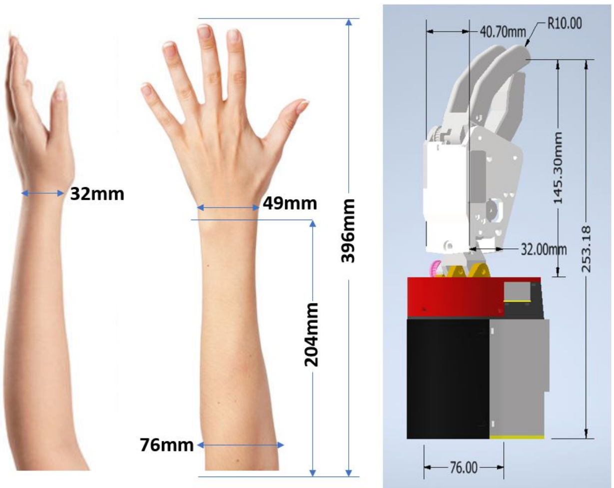

Fig. 1. The dimensions of UBArm in respective to the 25th percentile female arm including the hand [15]

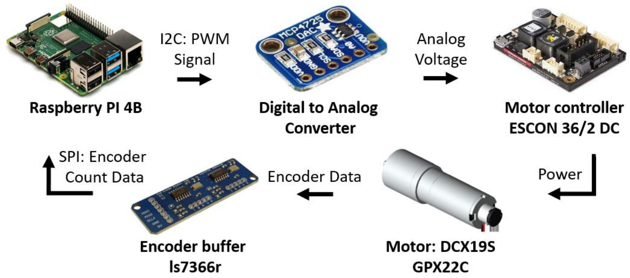

Fig. 2. Hardware diagram of the UBArm: Raspberry Pi sends PWM signal to DAC to control the ESCON motor controllers using Analog voltage. The motor position is tracked from the encoder feedback using the encoder buffer.

II. Transradial Prosthesis Design

A. Human Specification

The human wrist has specific set angle of rotation based on the DoFs available from the wrist. The angle rotations for the following wrist angles are respectively: 38° and 40° for Flexion and Extension; 28° and 38° for radial and ulnar deviation; 13° and 53° for pronation and supination [13]. These DoFs represent the full range of motion required to replicate the human wrist.

The dimensions of the UBArm is based on the 25th percentile female arm [14], [15]. The 25th percentile female arm dimension are portrayed in Fig. 1. The length from the elbow to the wrist is 204 mm. The circumference at the base of the elbow is 76 mm. The dimensions of the wrist are 49 mm by 32 mm. And the total length from the elbow to the tip of the finger to be 396 mm. Although the dimension mentioned include the entirety of forearm from the elbow to the fingertip, UBArm is a transradial prosthetic, thus a total length less than 396 mm is required. The 25th percentile female forearm also included the target weight of approximately 1.5 kg [5], [14], [15]. The target grasping distance is the length between the tip of the thumb and finger tips of the human hand. The grasping distance of the length 80 mm is required for a 25th percentile female hand [14]. The torque required to accomplish basic arm-based ADL task is set at around 1.5 Nm at the speed of 150 deg/s [16].

B. Hardware Selection

The hardware required for the UBArm was determined based on the specifications. Two DCX19S Maxon motors with a GPX22C gearbox with a gear of reduction of 231:1 and ENX10 encoder was selected. The Maxon motors had the capacity to run 1.6 Nm of torque and 311.7 deg/s continuously. The dimensions of the motor were 22 mm diameter by 74.5 mm. These motors were used to drive the PS and FE motion. In addition to the Maxon motors, two servo motors (Savox SV-1261mg) were used to for the gripper and RUD motion. These two servo motors can operate at 1.95 Nm at a max speed of 631.8 deg/s at intermittently. The dimensions are 48.5 mm by 30.7 mm by 15 mm.

The wearable electronics included the Raspberry Pi 4B as the main microcontroller, ESCON 36/2 DC motor controllers for the Maxon motors, digital-to-analog controller (DAC) board for digital to analog signal conversion, and an encoder buffer for an encoder counter. Analog Voltage control was used to control the Maxon motor speed through using the ESCON controllers. The Pi is unable to produce analog signal because all the output pins are General-Purpose input/output (GPIO) pins. GPIO pins can only be programmed to send digital signal. Thus, a DAC (MCP4725) board was required to generate an analog voltage signal for the ESCON controllers using I2C as the communication protocol.

The encoder from the Maxon motor is rated at 1024 CPR at max 30,000 rotation per minute (rpm). According to specification for the Maxon motor combination the maximum motor speed is at 12,000 rpm. Using the encoder CPR and maximum rpm, the sampling rate of 204,800 counts per second was calculated. In order to preserve accuracy of reading encoder signal, a sampling frequency of at least 2 times the sampling rate is chosen. Using the Nyquist frequency and the two different channels (channel A and channel B are offset by 90°), we need at least four times the sampling rate of the encoder to accurate read the encoder signal. Therefore, the data acquisition must be able to handle at least 819,200 Hz. The Pi has the ability to read high frequency, but has lower accuracy. This is due to the hardware limitation of the Pi. For the PI, counting for both encoder channels was computational demanding at high rpm. Therefore, an external encoder buffer (ls7366r) was utilized. The ls7366r is a 32-bit counter dedicated towards reading the encoder at a sampling frequency of 40 MHz. Using SPI communication protocol a MOSI and MISO was established between the PI and the encoder buffer.

C. System Configuration

The UBArm system can be configure in two different ways as portrayed in Fig. 3. The two modes of control are the AI Machine Learning (AIML) Mode and Manual Mode. The AIML mode uses the Trigno Delsys IMU/EMG Sensors. A python script uses the Trigno Delsys library to access the

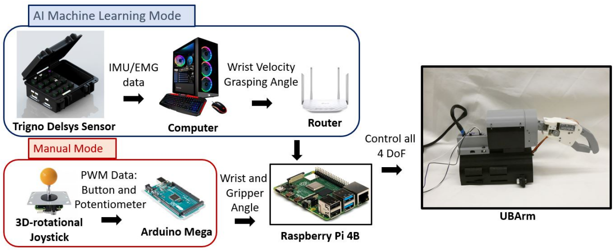

Fig. 3. Two System configuration modes: AI Machine Learning Mode predicting wrist velocity and gripper angle. The Manual Mode uses a 3-potentiometer joystick and buttons to map out wrist and gripper angle

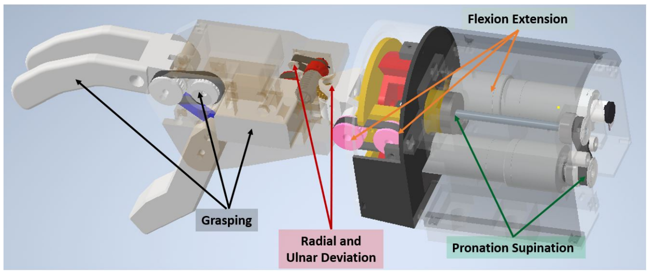

Fig. 5. Generated CAD model of the completed UBArm showing the mechanism location for Grasp, PS, RUD and FE

channels on the EMG/IMU sensors through a computer. A machine learning model can be used to predict the velocities of the prosthetic wrist DoF. The EMG sensor can be used on the flexor muscles to control grasping. The data is sent through the local network using a router to the Pi wirelessly. The Manual mode is a simple joystick that uses an Arduino microcontroller using UArt communication protocol. The joystick motion is mapped to the DoF wrist and grasping motion.

III. System Design

A. UBArm Specification

The completed prosthesis final specification is designed to encompass the specifications mentioned in previous chapter. The UBArm has 4 DoF, dedicating 3 DoF for the wrist and 1 Dof for the grasping. The weight of the prosthesis came out to be 0.75 kg. The bypass weight is 0.2 kg. The bypass is a wearable 3d printed brace that allows non-amputees to wear the prosthetic limb. The volume of the hand came out to be 1.89 x 10^5 mm^3. The forearm volume is approximate 5.16 x 10^5 mm^3. The UBArm is attached to the bypass fastened using nuts and bolts. The UBArm is placed at the front of the bypass as shown in Fig. 4a. The encoder buffer is located on the bypass right behind the UBArm. Cables from the prosthesis are routed about the arm up towards above the elbow where it is strapped between the elbow and shoulder in Fig. 4b. The cables continue to be routed towards the lower-back of the waist, where the battery and microcontroller are located.

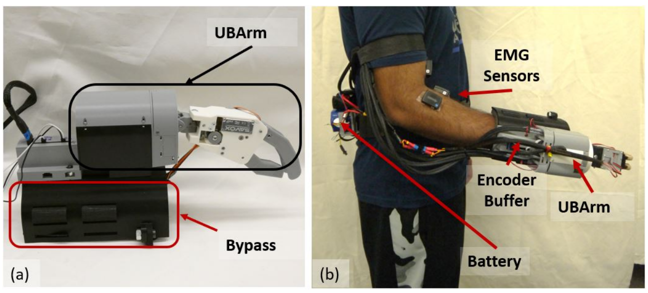

Fig. 4. (a) Completed UBArm, red represent the UBArm, blue represents the Bypass (b) The UBArm Worn with the EMG/IMU sensors, wearable electronics, and battery on the waist

The UBArm in Fig. 5, shows the different mechanism for each DoF. When considering the orientation and order of the wrist, it is crucial that the PS mechanism comes first. This is in order to replicate the human wrist motions. The other two motions can be in any order, but the PS mechanism must come first. Within the human wrist the FE motion and RUD motion rotates axially about the forearm. If any other orientation is used, the prosthesis will not be able to reproduce the human wrist motion.

B. Pronation and Supination Mechanism

The Pronation and Supination (PS) mechanism starts from the bottom base of the prosthesis. One of the Maxon motors are orientated as shown in the Fig. 6 is used in the PS motion. A system of belt gears, drive shaft, and PS base was required in order to actuate the PS motion. The belt gear is attached to the motor and drive shaft as so in Fig. 6. The belt gear was modified to fit a larger set screw using a tap. The belt was added along with a set of rollers to ensure tension shown in Fig. 6. Finding the right tension was key to reducing the likelihood of the belt slipping. This also increased the torque transmission across the motor to the end effector. The shaft is attached to the PS structure/base using a shaft hub. The ratio between the belt gear is 1:1, thus there is no reduction in speed or torque for the output. The PS is capable of range

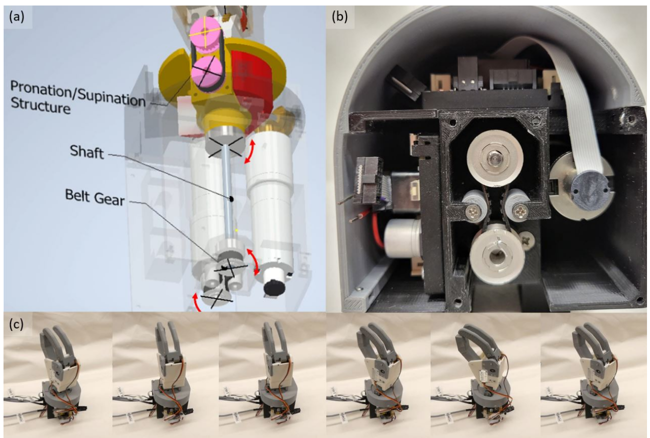

Fig. 6. (a) The CAD model shows the PS mechanism motions indicative by the red arrows (b) The PS motion belt and gears with idle rollers to tension the belt (c) PS Motion of the UBArm with max range of 15° pronation and 55° Supination

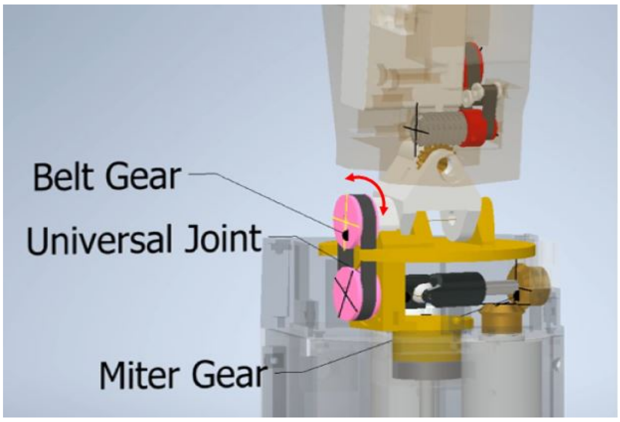

Fig. 7. Flexion Extension CAD model of the mechanism. The motor shaft is connected to the miter gears, Universal Joint, and belt gears

of motion from -15° to 55°, while running a 1 Hz reference signal. The PS motion is capable of producing up to 1.5 Nm. The max range of motion can be seen in both Fig. 6c. These figures show a comparison of pronation supination movement in the CAD model and UBArm.

C. Flexion Extension Mechanism

The Flexion Extension (FE) mechanism is unique and applies a joint mechanism that takes inspiration from Bandara's and Meng's designs using a universal joint ([10], [17]). Many different uncoupled mechanism ideas were explored in order to find the right mechanism for the FE motion. The FE motor had to either be coupled or physically rotated for it to produce the right motion. In order to independently move the actuator of all the DoF in the UBArm the universal joint was used. In Fig. 7 and Fig. 8, there are a set of Miter gears, u-joint, and belt gears in the FE mechanism.

The Miter gears in Fig. 7 is denoted by the brass color set of gears. The Miter gears transmit the torque from the motor to the universal joint (u-joint). The u-joint drives a set of belt gears that outputs the FE motion. The u-joint here serves a purpose which is crucial in maintaining the FE position. The PS motion can occur while the FE position does not move. This is the unique characteristic the u-joint that makes the FE mechanism work [17]. In Fig. 7 the u-joint is within the PS structure. The red dashed lines represent the center point in which a u-joint can freely rotate within a 90° range, or 45° range clockwise and counter clockwise. The FE motion end gear ratio was 1:1 capable of ranges from 40° to 40° from the initial position. It is capable of running at a 1 Hz signal and produce up to 1.5 Nm of torque.

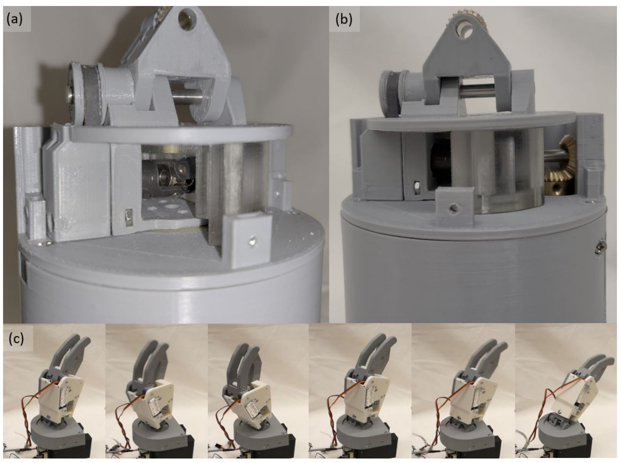

Fig. 8. (a) Universal Joint of the FE mechanism (b) Miter Gear of the FE mechanism (c) The motion of the Flexion Extension

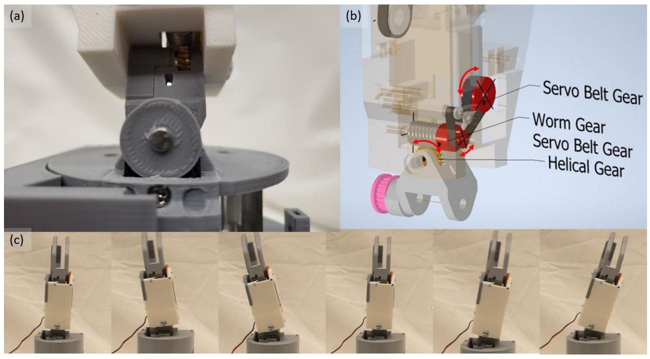

Fig. 9. (a) Worm and helical gear placement of the RUD mechanism (b) RUD CAD showing the mechanism movement indicative by the red arrows (c) The motion of the Radial and Ulnar Deviation

D. Radial and Ulnar Deviation Mechanism

The Radil and Ulnar Deviation (RUD) motion mechanism is located partial within the hand and partial on top of the end effector of the FE mechanism. The RUD mechanism is driven with a servo motor capable of producing up to 1.95 Nm. The end effector after the gear reduction comes out to be

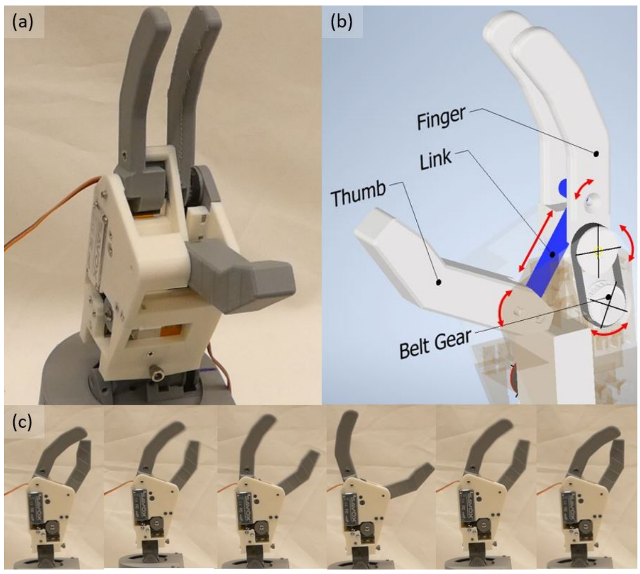

Fig. 10. (a) Grasping mechanism at max range of 90 mm (b) Grasping CAD showing the motions of the mechanism based on the red arrows (c) Motion of the Grasping from closed and open position

Name	Actuator	Control	Weight (kg)	DoF Wrist	DoF Hand	DoF Other
LUCS Haptic Hand III([7], [5])	RC Servo Motors	Tactile Sensors	–	1	6	0
RIC Arm [14]	DC Motors	EMG Sensors	1,518	2	2	1
DARPA Luke Arm (Transradial) ([7], [5])	DC Motors	Tactile Sensors, Myoelectric Sensors	1,270	3	15	0
Fluid Hand III [18]	Fluid Pressure	EMG Sensors	0.400	1	8	0
DEKA Arm([7], [5])	DC Motors	EMG Sensors	1.270	3	6	0
UBArm	DC & Servo Motors	EMG Sensors, Joystick	0.750	3	1	0

TABLE I

COMPARISON OF DIFFERENT PROSTHESIS WITH RESPECT TO THE TYPE OF ACTUATOR, CONTROL METHOD, WEIGHT OF THE PROSTHESIS, AND NUMBERS OF DEGREES OF FREEDOM

9.75 Nm. The RUD motion ranges from 28° to 38° radial and ulnar deviation angles respectively. The RUD motion can run at a 1 Hz reference signal. The RUD mechanism also uses a belt gear system and has a set of worm gear and helical gear. The belt gear is 3D printed using PLA and has a gear ratio of 2:1. The worm gear mechanism has a unique property, in which it can be non-backdrivable given a particular worm gear design. This property is advantageous and will allow the RUD position to be held at a given particular angle without actively using the servo motor [19]. This greatly reduces the energy consumption of the motor and can prolong the life of the actuator [19]. The worm gear ratio is a reduction of 1:10 ratio. The final gear ratio is a 1:5 reduction after considering both the belt gear ratio and the worm gear ratio.

The following RUD motion of the designed UBArm is shown in Fig. 9. Fig. 9(b) shows the belt gear rollers used to tension the belt. The rotation of the plastic belt gears gets translated to the worm gear. The worm gear then rotates about the helical gear axis. The helical gear does not rotate and is bolted onto the FE end effector.

E. Grasping Mechanism

The grasping mechanism utilizes a 4-bar linkage system to simulate the grasping motion of the hand. The Ottobock hand (8E37) also uses a 4-bar linkage system, which allows the grasping to be controlled using a single actuator [20]. The gear is attached onto the red finger as shown in Fig. 10.

A servo motor is also used to actuate the gripper in the hand. In Fig. 10, the belt gear on the bottom is attached to the servo, while the top belt gear is attached directly onto the finger. As the belt gears rotate, the finger also turns in the same direction. The motion of the finger is translated over to the thumb using a rigid link. The distance between the thumb and the finger is measured at 90 mm and can operate at a 1 Hz reference signal.

IV. COMPARISON WITH OTHER PROSTHETIC SYSTEMS

The development of the UBArm took numerous iterations due to the challenges of integrating all wrist DoF in small female forearm volume. The Raspberry Pi 4B was used to control servo motors, DAC boards, run a PID controller, obtain data from a computer using a local network, and count the encoder data at high frequency.

The UBArm was lighter than many of the state-of-the-art prostheses in table. I. The weight was recorded at 0.750 kg and had lower hand DoF in respect to the other prostheses. The Fluid Hand III, can be made an exception in this case because although the weight is recorded at 0.400 kg, the hardware for actuation was not included [18]. Fluid pressure requires additional system that can compress the fluid and basic solenoids that can control the flow of the fluid. The RIC Arm and Deka Arm are also prosthesis with lower weight than the 25th percentile female arm [7], [14]. Future research will be conducted to compare the user controllability of light-weight systems with high wrist DoF to those of heavier systems with high wrist and hand DoF.

V. CONCLUSION

Recently, the design of upper limb prosthetic hands has become increasingly complex and versatile, with a greater number of degrees of freedom. However, the prosthetic wrist often remains passive, or only has a single degree of freedom, leading to compensatory unnatural motion and resulting in pain and discomfort for the residual limb. A higher degree of freedom wrist, such as the UBArm, can significantly mitigate these issues. The UBArm is designed with a three-degree of freedom wrist and a one-degree of freedom hand, capable of executing pronation/supination, radial/ulnar deviation, and flexion/extension movements. Our aim is to create a highly functional wrist with a lightweight design that can improve the daily living activities of amputees and reduce unnatural motion for maximum comfort

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