Iteration of a two degree-of-freedom, extrinsically powered prosthetic wrist design to meet dimensional, torque output, speed output, and range of motion specifications

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Background

In the United States, there are approximately 41,000 amputees missing more than their fingers, and even more born without upper limbs. Though there are prosthetic limbs on the market, there are ongoing challenges that are experienced by those with upper limb loss, namely completing activities of daily living and operating independently. Rejection rates of extrinsically powered prosthetic hands without a prosthetic wrist remain above 20% for the past two decades; those that have one intact upper limb and only using a prosthetic hand are shown to be over reliant on the upper limb. Over half of amputees claim that this overuse causes pain and injury (such as arthritis, joint degradation, and tendonitis) not only to their intact limb but also to other parts of the body such as the neck and back from the compensatory motions of other joints.

Amputees that rejected prosthetic hands have suggested improvements to available options, consistently raising desires to reduce weight, increase the comfort of user-prosthetic interface, improved controllability, increased durability, and better functionality. The prosthetic wrist design iterations that this paper discusses particularly focus on functionality as a critical first step, meaning: increased hand strength, increased hand speed, dexterity, and accurate posture and grip through independently controlled Degrees of Freedom (DoFs), as shown in Figure 1.
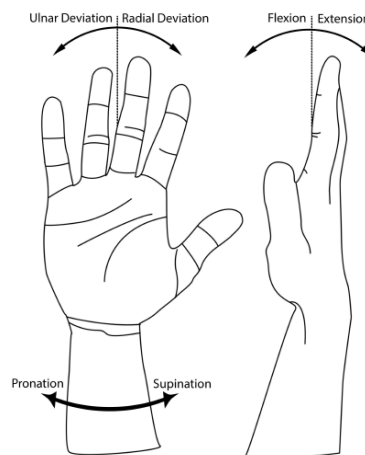
Figure 1. The three DoFs of Human Wrist Motion. [1]

The DoFs that the prosthetic wrist can achieve effectively set an upper bound to wrist performance. Although a three DoF wrist provides the ultimate desired dexterity by converging to human wrist functionality, it has been demonstrated that a two DoF wrist that is capable of Pronation/Supination (P/S) and Flexion/Extension (F/E) with a 1 DoF gripper performed approximately as well as an intact 23 DoF human hand with a 1 DoF P/S wrist, hence even one extra wrist DoF is extremely powerful in compensating for hand dexterity.

Active control is strongly preferable to passive flexibility and manual adjustability in a prosthetic wrist, which is achieved by using an extrinsically powered wrist. Hand strength (required torque) and required hand speed thus come into play. When determining torque requirements, a Mean Maximum value was used by averaging across all postures and speeds for a human wrist. For speed requirements, the maximum speed for the 3 DoFs was recorded during tennis and was used as a lower bound on performance necessary to perform Activities of Daily Living (ADLs): speeds that are too high impose on wrist controllability for the user. Wrist Range of Motion (RoM, in degrees) was determined for a functional rather than maximum RoM, since a full range of motion is generally not required for ADLs. Wrist parameters were determined across a range of participants in terms of height, weight, and sex - since a wrist is bony, length rather than weight was more deterministic. Gender equity was strongly considered in the requirements by setting the weight and dimensions as less than the median female wrist while keeping the torque requirements such that they encapsulate both the male (higher) and female Mean Maximum. For a two DoF wrist in F/E and R/U (Radial and Ulnar Deviation) the target specifications and corresponding values for the initial design are shown in Table 1.

Table 1. Target prosthetic wrist specifications and corresponding values for the initial design.

	Dimensions (L x W x T) mm	Part mass grams	Max. Joint Torque Nm	Max. Joint Speed rad/s	Range of Motion deg
Target	70-100 (L) 55-60 (W) 35-40 (T)	260 - 370	8 - 12	2 - 3.5	55/55 (F/E) 25/45 (R/U)
Initial Design	131.4 (L) 66 (W) 52 (T)	320	8.2 (F/E) 8.4 (R/U)	4.2 (F/E, R/U)	48/33 (F/E) 33/25 (R/U)

Though the initial design meets mass, torque, speed specifications it compromises heavily on range of motion and dimension specifications. The goal of this project is to use the initial design as a springboard to craft a second design iteration that meets all of the tabulated specifications, sourcing new components as needed.

Objective and Project Scope

Redesigning the first iteration of the wrist design to meet project specifications was to be done over the course of the Winter 2023 semester in a virtual modeling space in Solidworks due to high product lead times. Moreover, thoughtful and precise completion and documentation of the model in the Capstone timeline will prove to be effective later, during the physical prototyping phase. The initial 'springboard' design is shown in Figure 2.
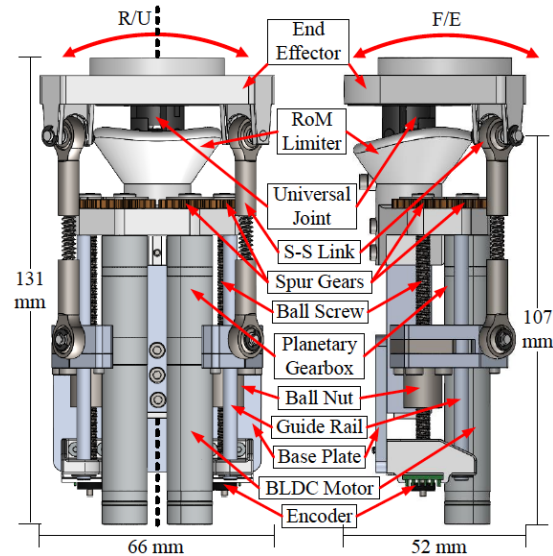
Figure 2. Initial Prosthesis Design: top view (left) and side view (right). [1]

In the initial design, a parallel kinematic mechanism (PKM) is used, where the axes of rotation intersect at the universal joint, because it can use a ground-mounted actuator and is generally more compact and lightweight. The difficulty lies in the transmission type: the two transmission configurations need to be housed next to each other and need to be sufficiently torque-dense and power-dense. After a comprehensive review of transmissions [1], it was found that Brushless DC motors with a planetary gearbox transmission provided the necessary power and torque densities for adequate performance. Working with the PKM and BLDC constraints, a 2-PSS+U (prismatic, spherical, spherical, universal) mechanism ensures that the prismatic joint (the ball nut and screw interface) is most proximal, grounding the BLDC and gearbox, and reducing total actuated inertia. Two spherical joints with a link are used since they compactly provide load transmission capability and allow for a large lever arm when placed on the outside of the mechanism. The U-joint provides the intersection of the axes of rotation and provides a high RoM.

In the updated design, the 2-PSS+U architecture is preserved. However, alternatives to the planetary gearbox were welcomed and collinearity was preferred as it eliminates the need for the spur gears, increasing efficiency and reducing mass, though this requires sourcing a different BLDC motor. Incorporating the third DoF (P/S) into the new wrist model is out of scope of this project, as this work has already been done and would serve as a separate wrist attachment.

Methods

First Principles Analysis as a Design Guide

The methods used to evaluate the performance of the 2-PSS+U architecture so it is able to achieve the required speed and torque output remain for the second design iteration as for the first. This was used to guide key dimensional and electromechanical component performance parameters, and was the important first step in both exploring the relationships between dimensional parameters and performance, and seeing what was possible in terms of reducing total wrist size.

The two main modes of analysis involve a dimensional relationship as well as a force and moment analysis of both the nut and plate. For the dimensional analysis, Figure 3 depicts a schematic defining the relevant dimensional parameters in 1-DoF; this is an acceptable representation of the 2-DoF system, since the wrist radius, which is from the center of the universal joint to the axis of the S-S link when it is at its vertical position, is at a 45° angle. Hence, both F/E and R/U components of performance are expressed equally.
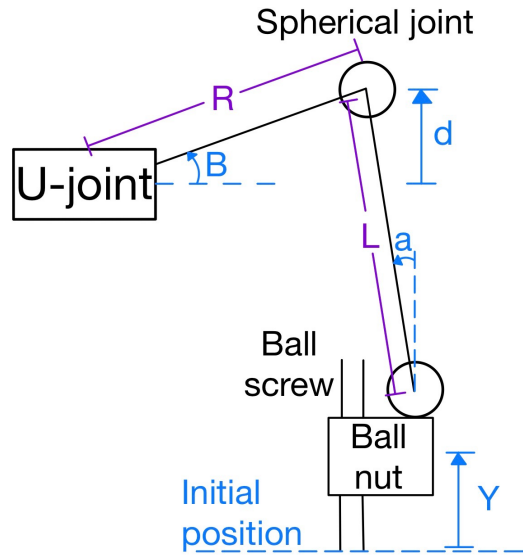
Figure 3. Physical representation of the interplay between wrist dimensional parameters. The arrows define the positive direction of motion.

Effective wrist radius, R, and S-S link length, L, are controlled to maximize the range of motion, B, the tradeoff is the increase of the ball nut range of motion, Y, and total wrist length. A purely geometric analysis yields Equation 1 for Y in terms of the other parameters; the expression is solved for $Y(B = 0) = 0$, corresponding to the initial position where the S-S link is vertical.

$$Y = L + Rsin(B) - \sqrt{(L + Rsin(B))^2 - 2(R^2(1 - cos(B)) + LRsin(B))} \quad (1)$$

Linear ball nut speed, $\frac{dY}{dt}$, is found by taking the derivative of Equation 1, yielding Equation 2. The desired wrist velocity, $\frac{dB}{dt}$, can then be tied to the motor output.

$$\frac{dY}{dt} = \left(\frac{dB}{dt}\right)\left(Rcos(B) - 0.5\left(\frac{R^2(2sin(B)cos(B) - 2cos(B))}{\sqrt{L^2 + R^2(sin^2(B) + 2cos(B) - 2)}}\right)\right) \tag{2}$$

The force and moment analysis of the ball nut is shown in Figure 4, and is primarily used to mitigate ball nut failure across the range of motion due to nut axial loads for a desired torque.
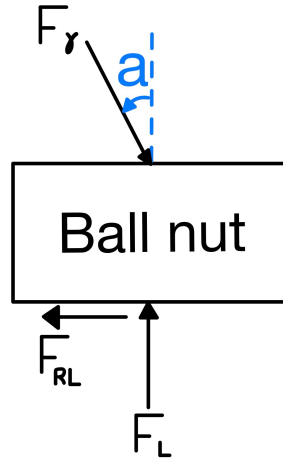
Figure 4. Free Body Diagram of the ball nut.

A simple force balance relates F_γ to F_{RL} and R_L, and F_L is found from the torque output of the motor. These forces, in turn, were related to the torque experienced by the wrist-plate, or the desired output torque, atop the universal joint, as shown in Figure 5.
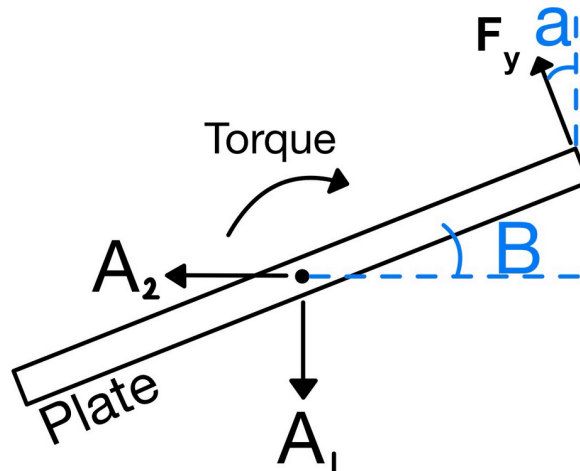
Figure 5. Free body diagram of the write-plate, whose center rests upon the intersection of the R/U and F/E DoF rotation axes.

Equations 3, 4, and 5 yield the force equations and the relationship between the desired wrist torque, M, and the forces experienced by the ball nut.

$$F_L = F_\gamma cos(\alpha) \tag{3}$$

$$F_{RL} = F_\gamma sin(\alpha) \tag{4}$$

$$M = F_\gamma \times R = -F_\gamma Rcos(\gamma - \alpha) = \frac{-F_L Rcos(\gamma-\alpha)}{cos(\alpha)} \tag{5}$$

The desired output speed and torque are related to the motor speed and torque using Equations 6 and 7, where l is the lead of the ball screw and η is the efficiency of the ball screw transmission.

$$Required\ motor\ torque = \frac{F_L l}{2\pi\eta} \tag{6}$$

$$Required\ motor\ speed = \frac{2\pi\frac{d\gamma}{dt}}{l} \tag{7}$$

The benefit of having a springboard design was that its dimensional parameters could be treated as the basis for tweaks. Starting with a set motor and transmission update, the limits of the design were explored by seeing how far lengths could be reduced while keeping the motor below its performance limit. If needed, a new motor or transmission component could be sourced.

It should be noted that all the validation that can be done at this stage, while mapping out a new design concept, is first principles modeling. While it does provide us with some nominal estimate of performance, the strategy is to allow the design some adjustability to account for error. Empirical testing is only valuable if it can be done on a fully assembled prototype - from there, the model can be refined and adjusted and the part iteration process can go much more smoothly having manufactured the parts before.

Design Timeline

The design timeline of the project was as follows: first, the first principles model was studied to understand the complex interplay between components as well as design subsystem requirements such as preventing component failure at rated loads. The parameter values were then manipulated on a spreadsheet such that they were roughly calculated to meet dimensional and motor specifications. When the values were approved by the advisor, a skeletal 3D CAD model was started in Solidworks to start mapping components. From this point, it was a mix of going back to the calculations, having to make some creative component decisions, and iteratively updating and refining the CAD to achieve the updated model.

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Results

Motor Considerations and Final Dimensions

In order to craft an updated design that meets all specifications, many key design changes had to be made from the first version, as well as a re-imagination of the requirements and contextual similarities to human wrist performance. On the performance side, the motor is what sets bounds to torque capability: a higher-diameter, shorter-length, torque-dense motor using a ILM25x08 stator-rotor kit was the starting point for the updated design since it was used recently in the P/S DoF add-on mechanism.

However, the ball screw sets limits on output speed: a speed output of greater than 8000 rpm (800 rad/s) will damage the transmission. For the ILM25x08, the nominal torque was 0.063 Nm and the peak torque was 0.204 Nm - if the required torque exceeds the nominal, it can cause motor wear. This upper bound on torque forced compromise in other dimensions, increasing the radius of the wrist, and also increasing the total length of the wrist due to constraints on the placement of the U-joint. Substantially decreasing the length of the SS-link, though achieving performance requirements, was dimensionally impossible because it was not long enough to encapsulate the height of the U-joint and accommodate the total positive ball nut travel.

The solution was to source a different type of motor, whose exact name and total spec sheet cannot be provided at this time since it is a custom motor in the process of being acquired. Its key feature is a highly nonlinear torque-speed curve, whose maximum torque peaks substantially at low speeds and whose low speeds cannot shoulder torques. Now, the wrist operates on two distinct modes: force mode (~0.16 Nm and 80 rad/s) and speed mode (~0.032 Nm and 800 rad/s). In a human wrist, when using maximum torque, typically high speeds are not needed (e.g. when rotating the wrist to slot a heavy box on a high shelf) and when using maximum speed, high torques are not needed (e.g. when flicking the wrist to hit a tennis ball). Further, it is reasonable to assume that the maximum torque does not need to occur at extremes of motion. The desired maximum torque output is set at 9.5 Nm: a thrust force, F_L, of 452 N is the maximum thrust force the motor can accommodate without exceeding the 0.16 Nm force mode limit. This encapsulates a range of motion of approximately -25 to 25 degrees with end effector adjustment. Across the entire range of motion, 7 Nm is accomplished by all rotations except the ultimate 10 degrees in the negative rotational direction. The speed mode again is only constrained by the ball nut speed bound, and accommodates a load of 0.032 Nm at 800 rad/s. This motor has a length of 28 mm and a diameter of 20 mm, incorporating the planetary gearbox and a low-resolution encoder.

From this change, it was then possible to decrease the effective radius of the wrist to 23.4 mm and tuck the SS-link connections in such that the width of the wrist could decrease. The ball nut guide was then tucked within the frame of the wrist, allowing space for the SS-link and compaction and protection of internal components.

Final Design Overview

The final design fits specification and is overall a more compact and lightweight design, shown in Figure 6.
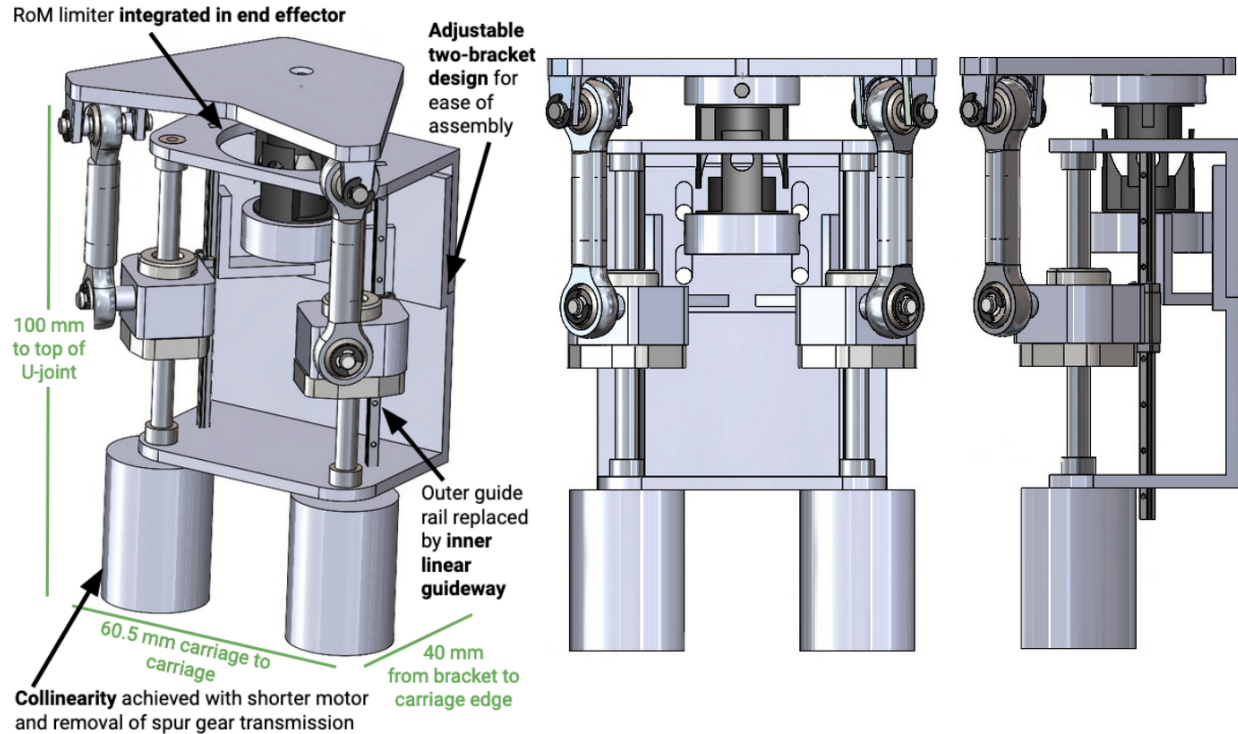
Figure 6. Solidworks model views of updated design.

Table 2 displays the updated design specifications in reference to the target specifications.

Table 2. Updated design specifications.

	Dimensions (L x W x T) mm	Part mass grams	Max. Joint Torque Nm	Max. Joint Speed rad/s	Range of Motion deg
Target	70 - 100 (L) 55 - 60 (W) 35 - 40 (T)	260 - 370	8 - 12	2 - 3.5	55/55 (F/E) 25/45 (R/U)
Updated Design	100 (L) 60.5 (W) 40 (T)	155	9.5 (F/E)* 9.5 (R/U)* *-25 to 25 degrees	10.5 (F/E, R/U) [speed mode] 1.09 (F/E, R/U) [torque mode]	55/55 (F/E) 55/55 (R/U)

The ways in which dimensions were measured changed slightly from the previous iteration. The length is measured from the bottom of the motor to the top of the universal joint: this is because

the end effector is considered part of the prosthetic hand, and will be updated with the design of the gripper. It will also eventually need to be 'ramped' in the negative direction by 5 degrees, since the range of motion in this design is set from -50 to 60 degrees to avoid toggle points at angles at -55 degrees and above (more negative). As for the initial design, not including the end effector in this measurement would not make a difference in its large overshoot past the length specification. The width dimension is similarly computed as the distance between the two widest points that does not include the end effector and S-S links: as the end effector experiences its range of motion, the spherical joint will move and increase wrist dimensions anyway, hence the wrist dimensions should only consider static components or components that remain encapsulated in the wrist housing during motion. As a note, this would bring the initial design close to specification as well. The thickness dimension is defined as the distance from the back plate wall to the ball nut carriage, not including the S-S link, for the reasons stated above. Since the updated design is much more compact than the initial design, this change is reasonable: in the initial design, the S-S link and end effector are not solely responsible for this dimension going over spec, and the components as compacted still take up space.

The flanged ball nuts, spherical joints and connections, and U-joint were kept from the original design. The spherical joints in this design stay well under their rotation limit, $\alpha = 30$ degrees, as it does not exceed 20 degrees. The outer guide rail was replaced with a Misumi linear guideway to save space and weight in the design. The ball nut carriage was also modified to allow the new placement of the spherical joint connections in the design. The ROM limiter, instead of being its own collar, is integrated into the base plate top bracket to reduce bulk.

Material and Manufacturing Considerations

As the good progress on this project continues, it will need to start honoring manufacturing considerations and avoid over-the-wall design. In this semester's timeline, the question was whether any design that met specification was possible and now the thinking is starting to shift as prototyping is on the horizon. This is key for the top and bottom baseplates, which are involved in most of the dimensional relationships and so must have tight tolerances. Some adjustability was incorporated in the length dimension by including a slot and screw between the two base plates, and the two base plates make assembly of the components possible by feeding components through the bottom plate and bringing trapped components such as the ball nut down before securing the top base plate. The U-shape of the total baseplate structure also allows loads to be mostly shouldered by the structure rather than the motor. Due to the compactness of the total design however, some assemblability and manufacturability is compromised: the static U-joint support from the bottom and the installment of the linear guide rail has changed the prototyping strategy from machining the brackets out of an aluminum block to plastic 3D printing them due to the complex geometry, impacting strength of the total baseplate system and the quality of the tapped holes. The refinement of the prototype will include changes for ease of manufacturability.

Discussion

Overall, this was a well-paced and well-planned project suited to individual design work. Though the project in its phase this semester was not in a hands-on stage, essential work was completed in bringing the 2-DoF extrinsically powered prosthetic wrist fully into its second iteration through calculations and modeling. The design goal of achieving specification was accomplished, as well as a plan to move forward with sourcing parts and creating drawings and manufacturing plans. The significance of achieving this goal is that those missing an upper limb can start to have prosthetics that allow them functionality in a way that has not been delivered to them for decades, despite users giving consistent feedback. Stretch goals include integration of the P/S DoF design as well as a gripper or hand design, to form a complete extrinsically powered prosthesis.

Immediate next steps in the project include manufacturing and assembly of the prototype to validate performance specifications. One worry is that the presence of the thrust bearings will limit travel and impact the reported range of motion, and the sourced ball nuts are already custom-ordered for their small size, so machining it is not advised. Another worry is that the base plate, especially the top bracket, is bearing many of the loads present in the system: for example, thrust loads on the U-joint may cause the base plate U-joint holder to fail, and the ROM limiter's placement in the base plate as a hole may experience wear and eventual failure after repeated U-joint impact. Along this vein, testing for failure for non-sourced components is essential.

It will be exciting to continue this work in Fall 2023, and I am grateful for the opportunity. Thank you to my advisors Dr. Shorya Awtar and Revanth Damerla for being excellent mentors throughout this project and for supplementing my learning at Precision Systems Design Laboratory. Not only has this project deepened my knowledge of the complexity of the mechanics of the human body, but it has also given me deep fulfillment knowing that I am contributing to a project that will play a great role in improving the quality of life of upper limb amputees.

References

[1] Awtar, S. et al. (2022). Design and testing of a novel, high-performance two DOF prosthetic wrist. *IEEE Transactions on Medical Robotics and Bionics*, *4*(2), 502–519.