Design and Prototyping of PIEJAM: a 2 Degree of Freedom Ankle Exoskeleton

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1 Introduction

This is a final report on the design and prototyping of Passive Inversion and Eversion Joint Ankle Mechanism(PIEJAM): a 2 degree of freedom(DoF) ankle exoskeleton.

Many ankle exoskeletons currently under development have only one DoF, which only allows plantarflexion and dorsiflexion. Our current ankle exoskeleton, PERL, is a prime example of a 1 DoF ankle exoskeleton[1]. While this may be sufficient for traversing level ground, inversion, and eversion movements are necessary to traverse uneven terrain and maintain balance. Therefore, the goal of PIEJAM was to design a 2 DoF ankle exoskeleton that would allow for both plantarflexion/dorsiflexion and inversion/eversion.

2 Project Requirements

The main specifications of this project, which PIEJAM must be able to satisfy, are as follows.

1. Provide an extra DoF to the ankle exoskeleton, allowing the user to perform inversion/eversion
2. Create adverse torque when pivoted
3. Limit the range of motion in inversion and eversion to prevent injuries to the ankle
4. Withstand the structural loads on the exoskeleton

The secondary specifications which the project should satisfy, are as follows.

1. Be comfortable and safe to use
2. Be easy to use
3. Be easy to maintain and repair
4. Have a low cost of production

Based on these specifications, a functional requirement chart is written. This chart specifies the function, its criteria, and the necessary numerical values if necessary. A K-factor score from 1-5 is given to each function to specify the importance of that particular function.

Based on the K-factor definition of table 1, the functional requirements of this project are specified.

IMPORTANCE	K-FACTOR
Useful	1
Desirable	2
Mandatory	3
Mandatory - Important	4
Mandatory - Very Important	5

Table 1: Definition of K-Factor

No.	Function	K	Criterion	Numerical Value
M1	Provide inversion and eversion DoF	5	Full inversion and eversion DoF	-
M2	Resistance to rotation	3	Must provide torque against inversion and eversion	$0.86N \cdot m/kg \cdot rad$ (Maximum, can be less)
M3	Limited range of motion	4	Limited range of motion of eversion and inversion	$20°$ (Can be less)[2]
M4	Structural Integrity	5	Resistance to eversion/inversion loads	$0.3N \cdot m/kg$ [3]
			Resistance to plantarflexion and dorsiflexion loads	Dorsiflexion: $0.45N \cdot m/kg$, Plantarflexion: $1.1N \cdot m/kg$[4]

Table 2: Main Functional Requirements

No.	Function	K	Criterion	Numerical Value
S1	Comfort and safety	5	User comfort	-
			Safety during use	-
S2	Ease of use	3	How easily the mechanism can be used	-
S3	Ease of maintenance	3	The difficulty in maintaining and repairing the mechanism	-
S4	Manufacturing cost	3	The cost of purchased and manufactured items	\$ 100
S5	Use of existing design	2	How well the design integrates with PERL	-

Table 3: Secondary Functional Requirements

3 Form Factor Selection

Before creating specific designs for the exoskeleton, various form factors were compared to determine the most optimal one. The form factors were defined using the key elements of any robot: joints and actuators. A typical robot uses joints like revolute joints, linear joints, universal joints, and spherical joints. Some common actuators include motors (rotational actuator) and linear actuators. The location and orientation of the joints and actuators define a basic configuration of the exoskeleton.

A total of four form factors were compared based on the functional requirements of the exoskeleton.

To have good comfort and mobility, the rotation axis of the ankle exoskeleton should match the rotation axis of the ankle. From biomechanics data, it is known that both dorsiflexion/plantarflexion and inversion/eversion have their rotation axis located along the ankle joint complex located in the center of the ankle. With the use of two revolute joints, the ankle exoskeleton structure becomes a 3-bar open chain, with the footplate being the first bar and the shank element being the last bar. This configuration leads to two designs depending on the order of the axis in the open chain.

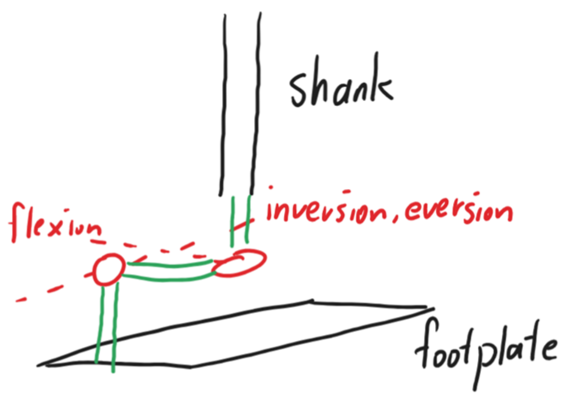

Figure 1: Design 1 has both revolute joint axes aligned with the ankle joint complex, with the inversion/eversion axis being attached to the footplate

Design 1: The first possible configuration with two aligned revolute joints is one where the inversion/eversion axis is attached to the footplate. A sketch of this configuration is shown in figure 1.

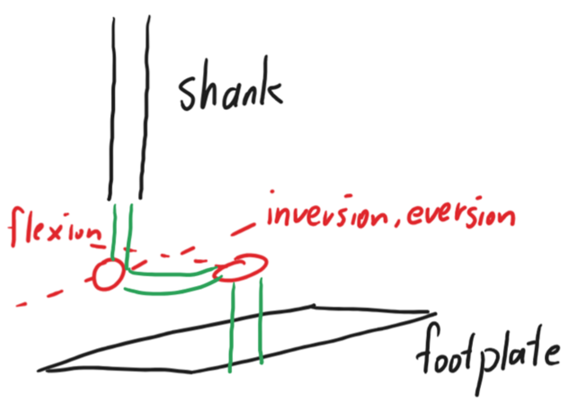

Figure 2: Design 2 has both revolute joint axes aligned with the ankle joint complex, with the dorsiflexion/plantarflexion axis being attached to the footplate

Design 2: The second possible configuration with two aligned revolute joints is one where the dorsiflexion/plantarflexion axis is attached to the footplate. A sketch of this configuration is shown in figure 2. It should be noted that this design requires the shank element to be located on the back of the shank, unless additional curves are added.

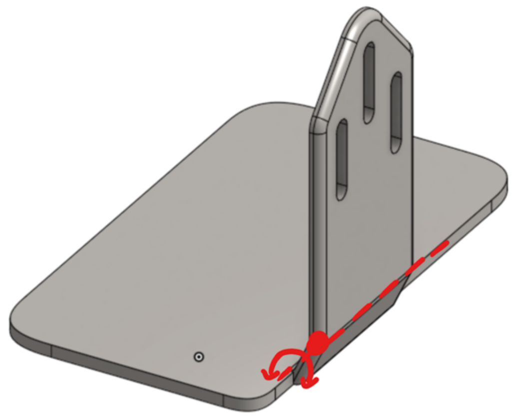

Figure 3: Design 1 has a revolute joint added directly to a typical foot plate which has a shaft on the outside of the shank that attaches directly to the footplate

Design 3: A common feature among ankle exoskeletons is the location of the main structural element: it is typically placed along the outer part of the shank, parallel to the sagittal plane[5] [6] [7] [8]. This means that the ankle exoskeleton must connect the footplate and a bar parallel to the shank on the outside of the shank. Our current ankle exoskeleton PERL is also of this configuration. The vast majority of existing 2 DoF ankle exoskeletons simply add a revolute joint to this shank piece. Figure 3 shows what that would look like on the PERL footplate. However, this creates a misalignment problem as the axis of rotation for inversion and eversion is close to the center of the ankle, not to the side.

Figure 4: LEFT: Design 4 which uses cable actuation for dorsiflexion/plantarflexion, RIGHT: Design 4-1 which adds an inversion/eversion cable to design 4 to create adverse torque

Design 4: This is a design that is inspired by ankle exoskeletons which use cables to actuate the dorsiflexion/plantarflexion axis[9]. Compared to designs that use a motor, this has the advantage of putting less weight on the foot. It also has minimal components around the foot and should be able to use existing shoes as a structural component. A modified design, denoted as design 4.1 uses additional cable actuation along the inversion eversion axis to create adverse torque. The motor's electromagnetic resistance should create the adverse torque necessary to provide feedback to the user.

The 4 configurations were evaluated using the functional requirements specified in table 2 and 3. The decision matrix criteria used are specified in the table below.

No.	Function	Criterion	Weight	Scale	Score
M1	Provide inversion and eversion DoF	Full inversion and eversion DoF	15%	Full 2-DoF	100
				Limited 2-DoF	40
				1-DoF	0
M2	Resistance to rotation	Must provide torque against inversion and eversion	10%	Provides resistance	100
				No resistance	0
M3	Limited range of motion	Limited range of motion of eversion and inversion	7%	Limited	100
				Unlimited	0
M4	Structural integrity	Resistance to eversion/inversion loads	10%	Good	100
				Okay	50
				Bad	0
		Resistance to plantarflexion and dorsiflexion loads	10%	Good	100
				Okay	50
				Bad	0
S1	Comfort and Safety	Comfort	13%	Comfortable	100
				Slightly Uncomfortable	60
				Uncomfortable	0
		Safety during use	13%	Safe	100
				Unsafe	0
S2	Ease of Use	How easily the mechanism can be used	5%	Easy to use	100
				Not easy to use	0
S3	Ease of Maintenance	The difficulty in maintaining and repairing the mechanism	5%	Easy to maintain	100
				Difficult to maintain	0
S4	Manufacturing cost	The cost of purchased and manufactured items	5%	High	100
				Medium	50
				Low	0
S5	Use of existing design	Can the existing PERL design be used?	12%	Can be used	100
				Cannot be used	0

Table 4: The decision matrix used to assess the preliminary designs

Based on the decision matrix, the score of each design was calculated. The grade of each design is shown in the figure below. Design 1, with a score of 87.3, received the highest score and therefore was chosen as the final design. While it did score lower than some designs on criteria such as structural integrity and comfort, it was the only design that would be compatible with PERL.

4 Compliant Mechanism Joint Design

The primary goal of PIEJAM is to provide an additional degree of freedom. Therefore, the joint mechanism is a central part of the exoskeleton's design. This joint must be able to withstand the

				Design 1		Design 2		Design 3		Design 4		Design 4.1	
No	Function	Criterion	Weight	Score	Normalized	Score	Normalized	Score	Normalized	Score	Normalized	Score	Normalized
M1	Provide inversion and eversion DoF	Full inversion and eversion DoF	15%	100	15	100	15	100	15	100	15	100	15
M2	Resistance to rotation	Must provide torque against inversion and eversion	5%	100	5	100	5	100	5	0	0	100	5
M3	Limited range of motion	Limited range of motion of eversion and inversion	7%	100	7	100	7	100	7	0	0	100	7
M4	Structural integrity	Resistance to eversion, inversion loads	10%	100	10	100	10	50	5	100	10	100	10
		Resistance to plantarflexion and dorsiflexion loads	10%	50	5	100	10	100	10	100	10	100	10
S1	Comfort and Safety	Comfort	13%	60	7.8	60	7.8	0	0	100	13	100	13
		Safety during Use	13%	100	13	100	13	100	13	100	13	100	13
S2	Ease of Use	How easily the mechanism can be used	5%	100	5	100	5	100	5	0	0	0	0
S3	Ease of Maintenance	The difficulty in maintaining and repairing the mechanism	5%	100	5	100	5	100	5	100	5	100	5
S4	Manufacturing Cost	The cost of purchased and manufactured items	5%	50	2.5	50	2.5	50	2.5	100	5	50	2.5
S5	Use of existing design	Can the existing PERL design be used?	12%	100	12	50	6	100	12	0	0	0	0
		SUM	100%		87.3		86.3		79.5		71		80.5

Figure 5: A table showcasing the scores of the designs based on the decision matrix

loads of the exoskeleton while providing the DoF in the inversion/eversion axis. It should also provide negative torque feedback, have limited range of motion to prevent injuries, and should be easy to manufacture and maintain.

Revolute joints typically consist of pins and bearings, with the use of torsional springs if adverse torque feedback is necessary. This increased number of parts adds complexity and cost to the overall design.

Instead, PIEJAM utilizes compliant mechanisms. These are flexible mechanisms that achieve force and motion transmission through elastic body deformation[10]. Compliant mechanisms have the advantage of using fewer parts to perform the movement. This reduces the cost and complexity of manufacturing and maintenance and allows the overall joint mechanism to be thinner and lighter.

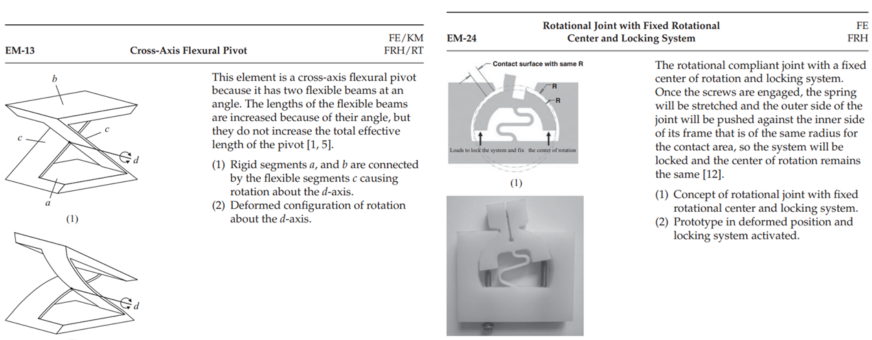

Figure 6: Two compliant mechanisms from the handbook used to design our joint[10]

Our compliant mechanism joint was inspired by two designs from the complaint mechanism handbook[10]. The cross-axis flexural pivot, on the left of figure 6, is the mechanism used to implement the rotational degree of freedom. It consists of two x-shaped bars, which are thin enough to bend, allowing the top and bottom segments to rotate about the center of the 'x'. This design provides rotational DoF and adverse torque feedback in one piece[11]. Design EM-24, on the right of figure 6, was used to form the overall shape of the mechanism. The inner circle and the outer circle are pushed to contact each other, which ensures a consistent center of rotation.

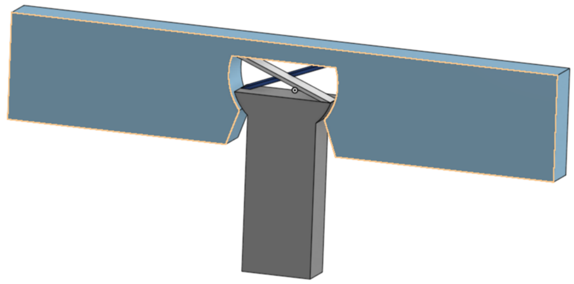

Figure 7: The design of our compliant mechanism joint

Furthermore, the design naturally limits the range of motion of rotation. The overall design of our mechanism is depicted in the figure below.

4.1 Joint Material Selection

The mechanical characteristics of a compliant mechanism depend heavily on the material used because its operation primarily involves deformations of rigid elements. For our design, the material should have sufficient stiffness to generate the necessary adverse torque when deformed. Additionally, the material should not be too brittle as the mechanism needs to withstand a substantial degree of strain.

The first versions of this joint (referred to as hinge from here on out) were printed using the Formlab Form 3+ resin printer. The resin printer was used because regular 3D-printed PLA was observed to be too brittle to be used for the hinge. Two resins were tested with this printer: the tough 1500 and the rigid 4000.

	6061 Aluminum	Tough 1500	Rigid 4000
Tensile Modulus	68.9 GPa	1.5 GPa	4.1 GPa
Ultimate Tensile Strength	310 MPa	33 MPa	69 Mpa
Tensile Strain at Break	17%	51%	5.3%
Flexural Modulus	68.9 GPa	1.4 GPa	3.4 GPa
Flexural Strength	310MPa	39 MPa	105 MPa
Flexural Strain at Break	17%	-	-

Table 5: Material Properties of resin, with Aluminum as reference

Table 5 shows the material properties of the resins, with the properties of Aluminum shown for reference[1][2][3]. Looking at the data, it is immediately clear that both the resins have much smaller tensile modulus compared to Aluminum. This means that with the same structure, the adverse torque generated by the resin hinge will be much smaller than the Aluminum hinge. Comparing the two resins, Tough 1500 has a much larger strain at break of 51% compared to just 5.3% for Rigid 4000. Hinges made using Rigid 4000 were observed to be too brittle for this application, so a strain at break value of at least 10% is recommended for our hinge design.

[1] https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6
[2] https://formlabs-media.formlabs.com/datasheets/2001292-TDS-ENUS-0.pdf
[3] https://formlabs-media.formlabs.com/datasheets/1801088-TDS-ENUS-0.pdf

	Onyx	Carbon	Fiberglass
Tensile Modulus	2.4 GPa	60 GPa	21 GPa
Ultimate Tensile Strength	40 MPa	800 Mpa	600 Mpa
Tensile Strain at Break	25%	1.5%	3.9%
Flexural Modulus	3.0 GPa	51 GPa	22 GPa
Flexural Strength	71 MPa	540 MPa	200 MPa
Flexural Strain at Break	-	1.2%	1.1%

Table 6: Material properties of Markforged printer materials

A second batch of hinges was printed using the Markforged Desktop series 3D printer. This is a 3D printer with the capability to print fiber-reinforced plastic by inserting fibers inside a medium called Onyx.

The material properties of Markforged printer materials are shown in table 6 [4]. The material properties of Onyx have values that are between those of Tough 1500 and Rigid 4000. It is more rigid compared to Tough 1500, with a tensile modulus of $2.4GPa$, but it isn't as rigid as Rigid 4000. It is capable of larger strains compared to Rigid 4000 at 25%, but isn't as good in this regard as Tough 1500. Carbon fiber reinforced Onyx has similar rigidity to Aluminum, but it is more brittle. Previous hinges printed with Tough 1500 were observed to be too flexible and unable to provide adequate torque feedback. However, it was not possible to print our hinge using carbon fiber reinforced Onyx, because our design was too small. Instead, the hinge was printed using only Onyx, and this is the hinge that is currently installed in the 2 DoF ankle exoskeleton prototype.

5 PIEJAM Design

This section describes the various dimensions and features of PIEJAM. The week-by-week design process and the various intermediate designs are documented in the PowerPoint presentation. Here, only the final version of the design is discussed.

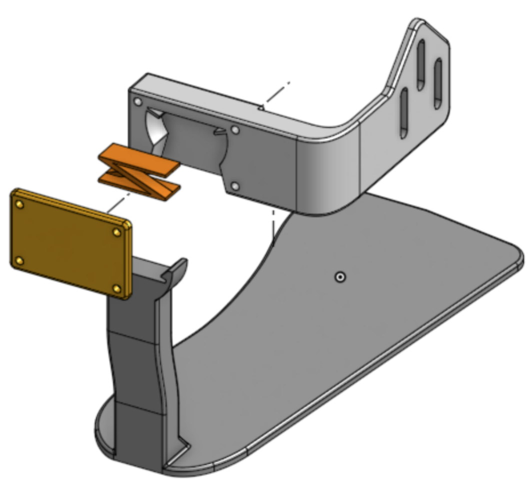

Figure 8: Exploded view of the 2 DoF Ankle Exoskeleton

[4]https://markforged.com/materials_geom=%E2%9C%AA

PIEJAM is made up of 4 parts. Each part can be seen in the exploded view in figure 8. The light grey part is referred to as the "upper part" and it connects directly with the PERL actuator. The dark grey part is referred to as the "lower part" and it consists of the footplate and the column. The part in orange is the "hinge", which as discussed in the previous section, provides the rotational degree of freedom and generates adverse torque. The part in yellow is the "cover" which goes over the hinge to prevent the column from moving backwards when performing plantarflexion.

5.1 Lower part

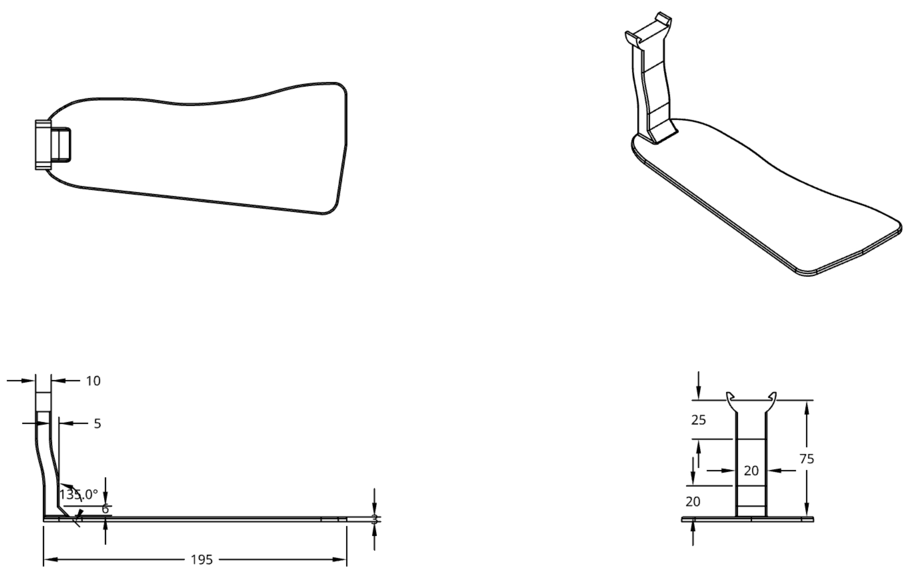

Figure 9: Drawing of the lower part(unit:mm)

The lower part consists of two parts: the footplate and the column.

The foot plate was designed and optimized on my own foot, and should therefore be modified to fit the needs of the user. It has a length of 195mm with a thickness of 3mm. The overall shape of the footplate starts narrow and becomes even narrower in the middle before widening towards the end. This shape ensures that all the areas of the foot that normally contact the ground are covered by the footplate. The foot plate only extends to the root of the toes, allowing the toes to bend while the foot is on the ground. A 1mm fillet was applied to the upper edges of the footplate to ensure the user would not detect any sharp edges.

The column has a rectangular cross section of 20mm by 10mm and has a height of 75mm. The edges of the column have a 1mm fillet to remove any sharp edges. An important feature of this column is that the column bends back 5mm. This is done to ensure that during plantarflexion, there is enough room between the exoskeleton and the back of the ankle. The column is attached to the footplate at the back, with a 6mm chamfer added to the base of the column for further structural reinforcement.

5.2 Upper Part

The upper part connects the lower part and the hinge to the PERL actuator. If we think of the exoskeleton as a 4-bar open chain, then the upper part is the bar that connects the inversion/eversion

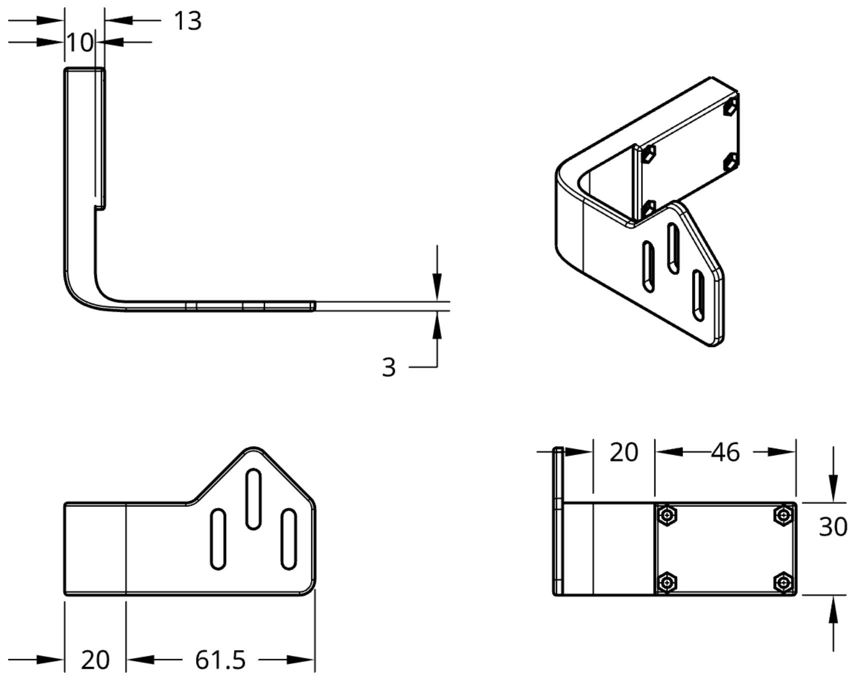

Figure 10: Drawing of the upper part(unit:mm)

joint to the dorsiflexion/plantarflexion joint. Since the two joint axes are orthogonal, the upper part has a L shape.

The geometries of the hinge attachment section will be discussed separately. This section has a thickness of 10mm, with a 3mm cover preinstalled on one side of the hinge. Flanking the four corners of the hinge are screw holes 3.1mm in diameter. These holes have a hexagonal end, which is designed to hold an M3 nut. A M3 screw 16mm in length is used in the screw hole.

The PERL attachment section was designed using the existing PERL footplate. This ensures that our design can be integrated into PERL. This section has a thickness of 3mm, which is identical to the original PERL footplate. All of the edges have a 1mm fillet to remove any sharp edges.

5.3 Passive Joint Section

The passive joints used in PIEJAM are a further development of the compliant mechanism joint design developed in figure 7. This is the section where the upper part, the lower part, and the hinge are assembled to create the inversion and eversion degree of freedom.

Figure 11 shows the sketch dimensions used to create the passive joint section(unit: cm). To understand the sketch, the steps taken to create the sketch must be described.

1. The center of rotation is defined to be 23mm away from the end of the upper part, and 10mm away from the top.

2. The radius of the hole of the upper part is set to 16mm, and the radius of the top of the lower part is set to 15.8mm. This leaves a 0.2mm margin.

3. The top wall inside the upper part is defined to be 5mm away from the top of the upper part itself.

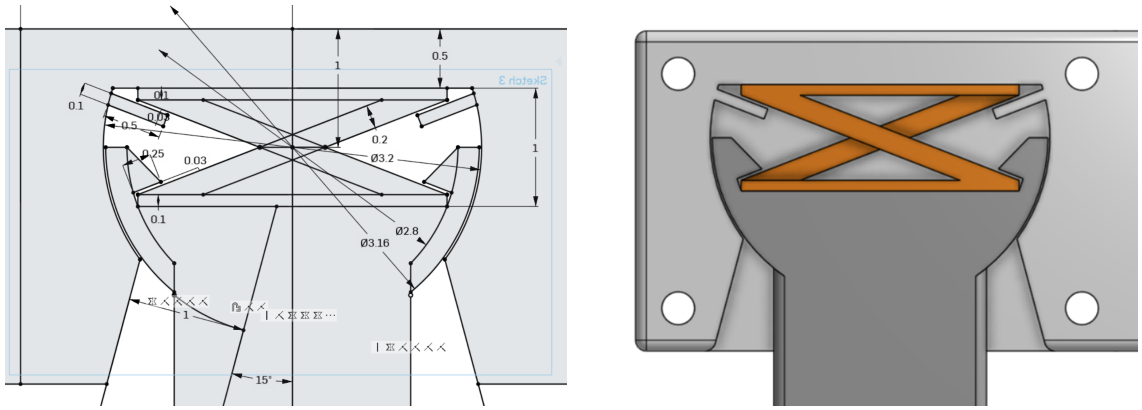

Figure 11: LEFT: sketch dimensions used to create the passive joint section, RIGHT: A depiction of the passive joint section

4. The inner radius of the top of the lower part is set to 14mm. This 1.8mm thick circular section extends to the horizontal line intersecting the center of the circle. This extension prevents the lower part from falling out of the hole inside the upper part.

5. The hinge is defined as an x-shaped plate with a height of 10mm. The width of the height is defined by the other sketch features such that it fits exactly inside the gap between the two circular teeth of the lower part. The thickness of the top and bottom plates is 1mm, and the thickness of the x-shaped hinge itself is 2mm.

6. As the column of the lower part is 20mm wide, its edges are 10mm away from the vertical center line. The edges of the wall to the side of the columns are at 15° and positioned to perfectly line up with the column when it rotates about the center of rotation.

7. A pair of teeth are added to both the upper and lower parts to hold onto the hinge. The dimensions of the teeth are shown in figure 11. The gap between the teeth and the hinge is set to 0.3mm to ensure that it isn't a tight fit.

This joint design satisfies many of the initial requirements. The use of the compliant joint mechanism creates the desired degree of freedom and generates negative torque feedback. The location of walls of the hole, and the extension of the circular section of the lower part ensures that the range of motion is limited to around 15°. As all of the parts are inside the same plane, and encased by plates on both sides, the structural properties are also satisfied. Finally, the overall design only uses three parts and does not use any screws or lubricants, making it simple to manufacture and maintain.

5.4 Hinge

The hinge is an x-shaped piece designed to warp such that the part on the top rotates about the center of the piece. The dimensions of our hinge are shown in figure 12. The hinge has a length of 26.3mm (defined by other features of the joint section), a width of 10mm, and a height of 9.6mm. While the joint section sketch defined the height of the joint as 10mm, a 0.4mm gap was created to further enlarge the circular gap between the lower part and the upper part, which reduces the torque generated by friction. each arm of the 'x' is 2mm thick and 4.5mm wide. This creates a

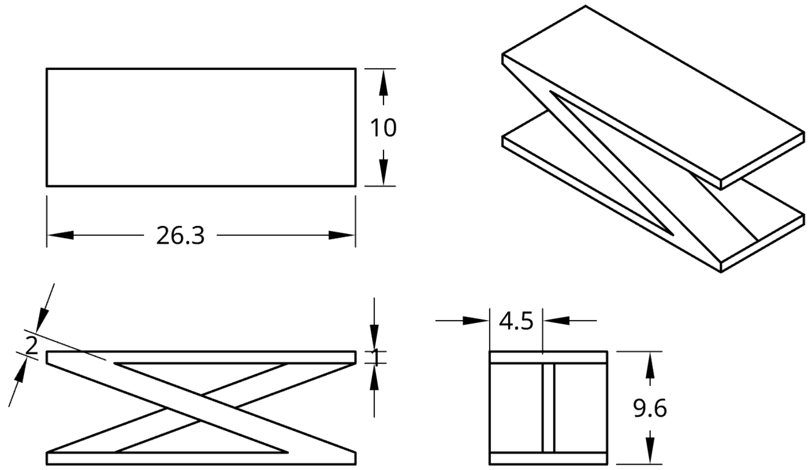

Figure 12: Drawing of the hinge(unit:mm)

1mm gap between the two arms which ensures that the two arms are not attached to each other. It was observed that having the two arms attached in the middle results in the stress and strain being focused in the center, leading to the structural failure of the hinge.

5.5 Cover

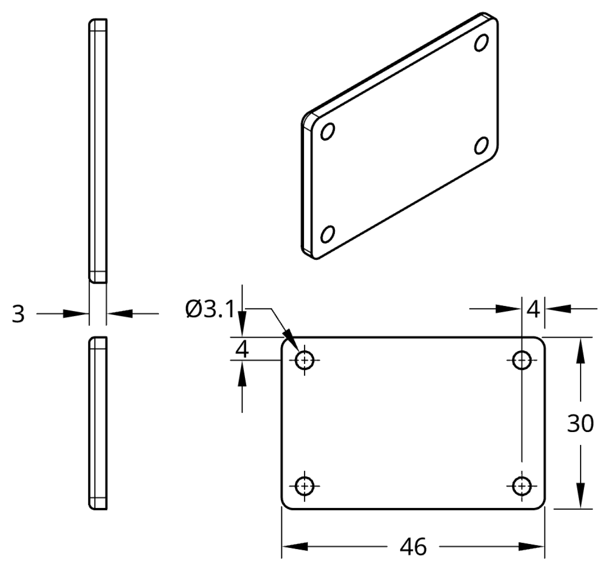

Figure 13: Drawing of the cover(unit:mm)

The cover is a simple rectangular plate that ensures that the column of the lower part stays within the hole of the upper part. It has a length of 46mm, a width of 30mm, and a height of 3mm. There are four screw holes on each corner of the rectangle, located 4mm away from the edge. The holes have a diameter of 3.1mm and are designed to be used with M3 screws. The cover attaches to the upper part using 4 M3 screws 16mm in length, with M3 nuts at the end to hold the screws in place. The edges have a 1mm fillet and each corner of the rectangle has a 2mm fillet.

6 Necessary Improvements

There are aspects of the current design that need improvement. There are also deficiencies in the current prototype and the manufacturing process that need to be addressed. This section addresses these topics.

- The current hinge design printed in Onyx has good negative torque feedback, but more feedback may be better. This can be addressed by using stiffer materials like Aluminium.
- The top of the upper part contacts the back of the heel during plantarflexion, which over time may create abrasion bruises. This issue could be addressed by adding foam to this part.
- Despite the 0.1mm of tolerance in the screw hole and nut hole, it is still a tight fit. More tolerance or extra sanding is necessary.
- The gap between the 'teeth' and the top of the hole in the upper part has supports inside when printed. These supports are difficult to remove, and as a result, the hinge is not able to be inserted all the way in the current prototype.

References

[1] A. Gesta, S. Achiche, and A. Mohebbi, "Design considerations for the development of lower limb pediatric exoskeletons a literature review," *IEEE Transactions on Medical Robotics and Bionics*, 2023.

[2] R. P. Kleipool and L. Blankevoort, "The relation between geometry and function of the ankle joint complex: a biomechanical review," *Knee surgery, sports traumatology, arthroscopy*, vol. 18, pp. 618–627, 2010.

[3] T. W. Kaminski, D. H. Perrin, and B. M. Gansneder, "Eversion strength analysis of uninjured and functionally unstable ankles," *Journal of athletic training*, vol. 34, no. 3, p. 239, 1999.

[4] T. A. Wren and J. R. Engsberg, "Normalizing lower-extremity strength data for children without disability using allometric scaling," *Archives of physical medicine and rehabilitation*, vol. 88, no. 11, pp. 1446–1451, 2007.

[5] N. Aliman, R. Ramli, and S. M. Haris, "Design and development of lower limb exoskeletons: A survey," *Robotics and Autonomous Systems*, vol. 95, pp. 102–116, 2017.

[6] S. Hussain, P. K. Jamwal, and M. H. Ghayesh, "State-of-the-art robotic devices for ankle rehabilitation: Mechanism and control review," *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, vol. 231, no. 12, pp. 1224–1234, 2017.

[7] A. Plaza, M. Hernandez, G. Puyuelo, E. Garces, and E. Garcia, "Lower-limb medical and rehabilitation exoskeletons: A review of the current designs," *IEEE Reviews in Biomedical Engineering*, vol. 16, pp. 278–291, 2021.

[8] A. Rodríguez-Fernández, J. Lobo-Prat, and J. M. Font-Llagunes, "Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments," *Journal of neuroengineering and rehabilitation*, vol. 18, no. 1, p. 22, 2021.

[9] H. Xia, J. Kwon, P. Pathak, J. Ahn, P. B. Shull, and Y.-L. Park, "Design of a multi-functional soft ankle exoskeleton for foot-drop prevention, propulsion assistance, and inversion/eversion stabilization," in *2020 8th IEEE Ras/Embs international conference for biomedical robotics and biomechatronics (Biorob)*, pp. 118–123, IEEE, 2020.

[10] L. L. Howell, S. P. Magleby, B. M. Olsen, and J. Wiley, *Handbook of compliant mechanisms*. Wiley Online Library, 2013.

[11] B. D. Jensen and L. L. Howell, "The modeling of cross-axis flexural pivots," *Mechanism and machine theory*, vol. 37, no. 5, pp. 461–476, 2002.