Hardware Interface Design for Power Tools to Exoskeleton

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Declaration

I assure that I have written this work autonomously and with the aid of no other than the sources and additives indicated.

Munich	15.06.2022	
Place	date	Signature

Project Note

Semester Thesis	No. 0085
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My supervisor Dr. Anand Sureshbabu mentored me during the compilation of the work and gave continuous input. We exchanged and coordinated approaches and results biweekly.

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Contents

1 Introduction

In recent years, the issue of work-related injuries has attracted more and more attention from society, among which, musculoskeletal disorders (MSDs) may pose the greatest threat to workers' health.

According to the U.S. Bureau of Labor Statistics, musculoskeletal disorders (MSDs), sometimes called "ergonomic injuries", occur when the body uses muscles, tendons, and ligaments to perform tasks, oftentimes in awkward positions or infrequent activities which over time can create pain and injury. Overexertion and repetitive motion are the primary causes of these injuries. *(U.S. Bureau of Labor Statistics 2019)*

Chart 1 from the U.S. Bureau of Labor Statistics indicates that while the percentage of MSD cases in all DAFW(days away from work) cases decreased between 2011 and 2018, the number of days absent from work due to MSDs has increased slightly.

Chart1-1: Number, incidence rate, and median days away from work of injuries and illnesses involving musculoskeletal disorders, U.S., private sector, 2011-18

Year	Number	Incidence rate	Median days
2011	311,840	35.4	11
2012	316,740	35.1	11
2013	307,640	33.5	11
2014	298,460	31.9	13
2015	286,350	29.8	12
2016	285,950	29.4	12
2017	282,750	28.6	13
2018	272,780	27.2	12

Source: the U.S. Bureau of Labor Statistics, 2019

In addition, the problem of MSDs has had a significant economic cost to employers and society, in association with absenteeism, loss of productivity, increment in health care costs, compensation costs, and a higher chance of disability. In the case of the United States, estimations have been made that at least 1 billion dollars per week are paid by employers for direct workers' compensation costs for disabling, nonfatal workplace injuries in 2018. *(Business Case for Safety and Health - Overview | Occupational Safety and Health Administration 2022)*

Therefore, the issue of MSDs must be considered with utmost seriousness.

1.1 Problem

In some specific industries, such as aerospace assembly, logging, and construction, MSD conditions are particularly common. Laborers engaging in these industries share a similar nature of work, which is using vibrational power tools, like riveting guns, chain saws, hammer drills, and so on, with high intensity.

This Project chooses construction workers who are involved with various types of power drills in their daily work as reference subjects. Because firstly the frequency of health problem reports from construction workers is relatively high and secondly, the wide range of power tools used on construction sites are also commonly used by non-construction worker groups in domestic life.

Among a wide variety of MSDs may occur, the most common ones are Carpal tunnel syndrome *(CTS)*, Back injury & back pain, Arthritis, and vibration white finger*(VWF)*. *(Work-Related Musculoskeletal Disorders & Ergonomics | Workplace Health Strategies by Condition | Workplace Health Promotion | CDC 2022, S.1)*

In the midst, shoulder arthritis*(Figure 1-2)* and vibration white finger*(Figure1-3)* are the main focus of our attention, as shoulder arthritis can be induced by long-term muscle fatigue caused by prolonged operation of weighted power tools, and vibration white finger is often originated from rotational and shock vibration upon interfacing with a power tool. Examples of the typical power tools used in the construction industry are demonstrated in *Figure1-1*.

(a)

(b)

(c)

Figure 1-1: Typical power drills: (a)Makita HR140D: hand drill with hammer function(Makita 2022) (b)Makita DF332D: hand drill without hammer function(DF332D - Akku-Bohrschrauber 2022) (c)Hilti TE 60-A36: hand drill with hammer function (Hilti Deutschland 2022)

Detailed descriptions for shoulder arthritis and vibration white finger are discussed below.

Shoulder arthritis is defined as damage to the cartilage inside the shoulder joint. When the cartilage in the shoulder begins to break down on the surface and eventually in the deeper layers, it's called shoulder arthritis. *(hopkinsmedicine.org 2021)* As shown in *Figure 1-2*, there are four stages of shoulder arthritis. In the first stage, the cartilage gets soft. Then, it develops cracks in the surface. Afterward, it begins to "fibrillate" *(deteriorate and flake)* Finally, it loses its ability to act as a smooth, gliding surface.

Different types of shoulder arthritis are associated with different causes, and some causes are still unknown. Osteoarthritis, also known as degenerative joint disease, is often related to wear and tear in connection with age. Rheumatoid Arthritis has its root in the immune system. Post-Traumatic Shoulder Arthritis is in tight relation with fractures, dislocation, or other injuries. Rotator Cuff Tear Arthropathy is a type of shoulder arthritis that can develop after a massive and prolonged rotator cuff tear. Or, there are possibilities that shoulder arthritis can be induced by Avascular Necrosis. *(hopkinsmedicine.org 2021)*

In conclusion, long-term factory work using power tools with unpleasant working positions can give rise to wear and tear, further triggering certain kinds of shoulder arthritis.

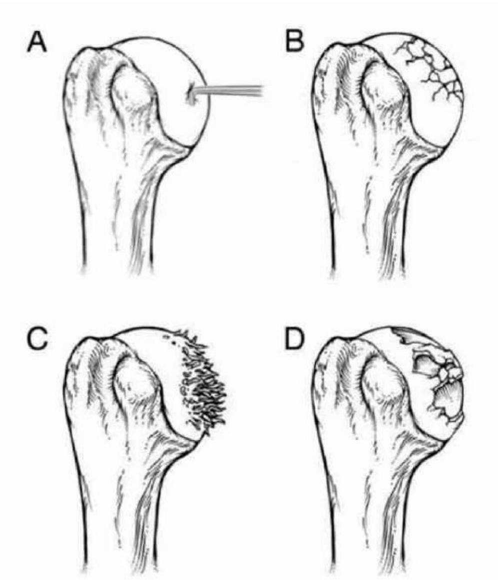
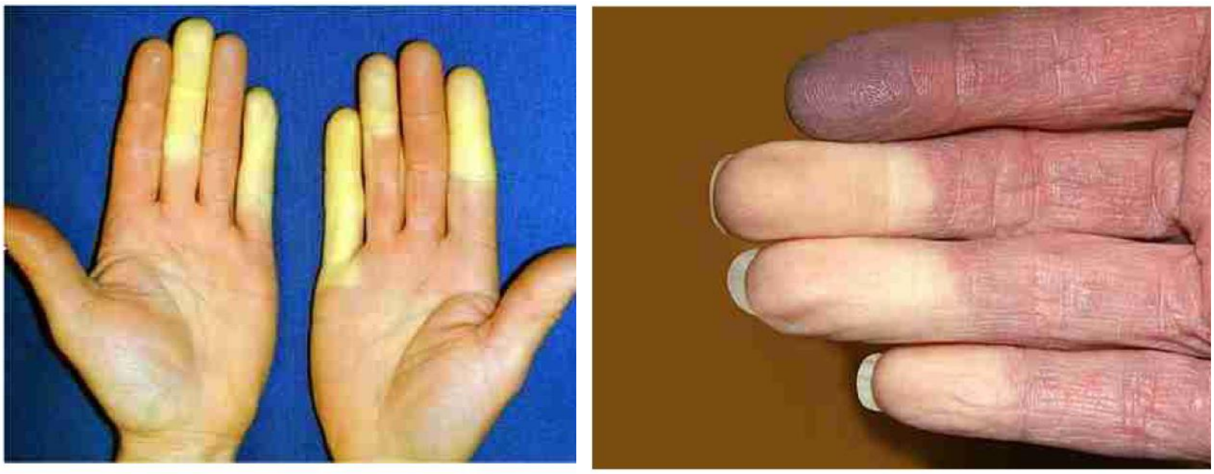


Figure 1-2: Four stages of shoulder arthritis. (A)First, the cartilage gets soft (B)Then, it develops cracks in the surface (C)Then, it begins to "fibrillate" (deteriorate and flake) (D)Finally, it loses its ability to act as a smooth, gliding surface (hopkinsmedicine.org 2021)

Vibration white finger *(VWF)*, also known as hand-arm vibration syndrome *(HAVS)* or dead finger, is a secondary form of Raynaud's syndrome, an industrial injury triggered by continuous use of vibrating hand-held machinery. Effects include tingling 'whiteness' or numbness in the fingers *(blood vessels and nerves affected)*, fingers changing color *(blood vessels affected)*, and loss of manual dexterity *(nerves and muscles affected)*.

Injury can occur at frequencies between 5 and 2000 Hz but the greatest risk for fingers is between 50 and 300 Hz. The total risk exposure for hand and arm is calculated by the use of ISO 5349-1, which stipulates maximum damage between 8 and 16 Hz and a rapidly declining



(a) *(b)*

risk at higher frequencies. *(Wikipedia 2022c)*

Figure 1-3: Symptons of Vibrational White Finger (Voelter-Mahlknecht et al. 2012; Eldred Law 2022; Voelter-Mahlknecht et al. 2012) (a) Overall look of VWF symptoms (b) Close look of VWF symptoms

1.2 State of the art

For the prevention and control of possible MSDs, a three-tier approach has been widely accepted as an intervention strategy to lessen the effect of workplace hazards. Under the recommendation of the U.S. CDC *(Work-Related Musculoskeletal Disorders & Ergonomics | Workplace Health Strategies by Condition | Workplace Health Promotion | CDC 2022, S.3)*, the three-tier intervention approaches are as follows:

- Use of engineering controls

The most efficient way to prevent and control MSDs is to design the job to meet the capabilities and limitations of the workforce using engineering methods. Examples include changing the way materials, parts, and products are being transported, and changing the workstation layout.

- Use of administrative controls *(changes in work practices and management policies)*

Policies and practices can help to reduce the MSDs risk but don’t eliminate workplace hazards.

- Use of personal protective equipment *(PPE)*

PPE*(such as braces, wrist splints, back belts, and similar devices)* provides a barrier between the worker and the hazard source.

In the field of mechanical engineering, attempts at occupational disease prevention and control usually incorporate both methods of engineering control and personal protective equipment. In order to reduce the work fatigue caused by static load, industrial exoskeletons are widely accepted as a solution. A wide variety of institutes around the globe have made contributions to this field *(Bao et al. 2019)*. Parallel to that, several approaches exist for damping the vibration caused by the use of power tools.

1.2.1 Industrial exoskeletons aiming at static load compensation

An exoskeleton is a wearable device in which the physical contact between the operator and the mechanical structure allows a direct exchange of mechanical power and information signals. The technology has its roots in military and rehabilitation fields, but its use in industry is becoming increasingly sophisticated. *(Spada et al. 2018)*

A rough classification of industrial exoskeletons can be made from several perspectives. Depending on whether one is reliant on external energy sources, wearable devices can be divided into passive and active types. Regarding the main attachment point of the exoskeleton, it can also be categorized as upper-limb, lower-limb, or full body.

Large international companies like Lockheed Martin have developed their industrial exoskeleton platform FORTIS specifically for the aerospace assembly industry. FORTIS platform transfers loads through the exoskeleton to the ground in standing or kneeling positions and allows operators to use heavy tools as if they were weightless. *(Lockheed Martin 2021)* In terms of classification, it is a lower-limp, passive exoskeleton.

(a) (b)

Figure 1-4: FORTIS Exoskeleton (a) Standing position (b) Kneeling position (Lockheed Martin 2021)

Smaller companies like Esko bionics have delivered a completely different solution by releasing their newest version of EVO. It is an upper-limb, active and lightweight exoskeleton.

(a) *(b)*

Figure 1-5: (a) Man holding a drill in overhead working position wearing EVO (b) EVO assembly stand-alone (Ekso Bionics 2022)

1.2.2 Vibration control

Vibration control is a set of technical means to reduce the harm of vibration. Two specific ways are possible, one is passive, and the other is active.

Passive vibration control is considered a more traditional approach, using vibration dampers, shock absorbers, and base isolation, whose aim is to dissipate the energy that is transmitted from the vibration source to the object which needs to be isolated. A typical means of passive vibration isolation is anti-vibration gloves*(Figure 1-6)*. The damping material attached to the palm helps absorb energy, enabling vibration isolation.

Figure 1-6:Typical anti-vibration gloves (Lightweight Anti-Vibration Gloves | Ergodyne 2022)

Active vibration control is the active application of force in an equal and opposite fashion to the forces imposed by external vibration. *(Wikipedia 2021)* In practice, active vibration control usually requires a complete feedback control system, including sensors, controllers, and actuators, making it a complex mechatronic system.

Bosch however, has succeeded in implementing an active vibration control mechanism in the reciprocating motion mechanism of one electric saw that relies solely on mechanical construction, which is very impressive work. The concept is shown in *Figure 1-7*.

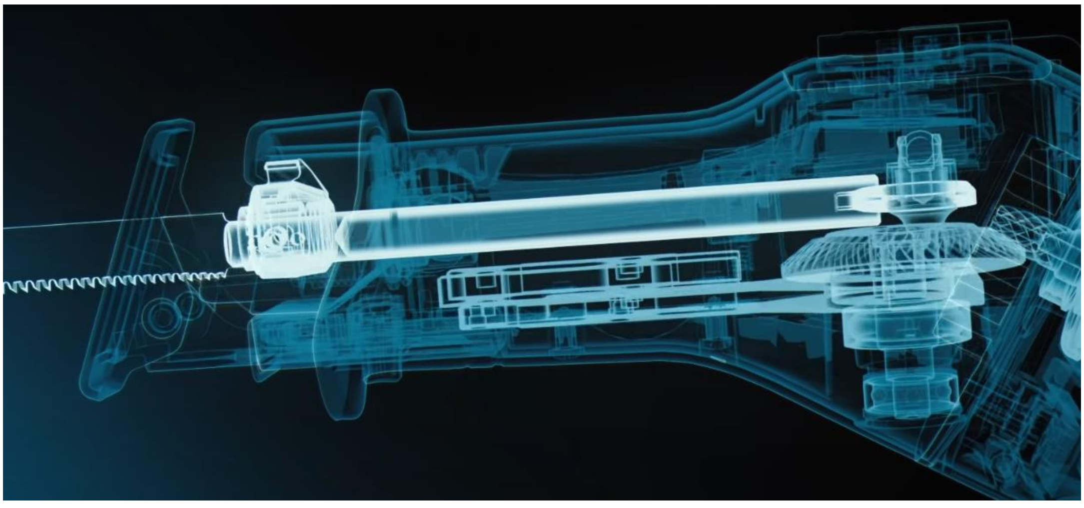


Figure 1-7: Active vibration control based purely on mechanical construction(Bosch-protection 2022)

1.3 What do we solve?

Existing technology usually treats static load compensation and vibration damping separately. However, in real-life application scenarios, these two problems often arise at the same time. Generally speaking, heavier power tools will bring more intense vibrations. If the tool user needs full protection, he/she can only work with two kinds of auxiliary products for gravity compensation and vibration damping respectively, causing a heavy weight burden in the meantime.

Therefore, the main objective of the project is made clear, to design a device capable of achieving gravity compensation and vibration reduction simultaneously. Aside from these two main functionalities, attractiveness, wearability, comfort, crowd adaptability, and expandability are all factors to be taken into account.

2 Development Process

In this section, the development process of Wearable-Power-Tool*(WPT in short)* will be described in detail. The whole development process can be divided into three stages, which are concept design, embodiment design, and detail design. In the end, the topic of tests & experiments is included.

2.1 Concept design

The development process starts with concept design. In this stage, primary concepts are collected through analysis of user needs and brainstorming.

The fundamental aim of building this prototype was to assemble a wearable platform for holding the drill so that it could provide sufficient degrees of freedom for the horizontal and overhead working position.

For wearability design, the upper arm anatomy and potential design challenges are acquired through a literature survey. *(Gull et al. 2020)*

At the same time, the platform would have to perform some degree of static load compensation*(no less than 50%)* in order to reduce worker fatigue when working with power tools. In an effort to achieve static load compensation, we have introduced a universal exoskeleton vest, very commonly used in the photographic industry*(shown in Figure 2-1)*, to transmit the load received by the forearm to the entire upper body torso.

Where possible, prevention of the occurrence of the vibrational white finger is preferred by somehow damping the vibration transmission from the drill to the worker's hand and forearm.

In addition, the prototype should also be able to work without an external exoskeleton, requiring the whole structure to be lightweight.

The name "Wearable-Power-Tool" has been given to this general concept. In the next sections, WPT will appear as an abbreviated form of Wearable-Power-Tool.

Figure 2-1: Flycam Galaxy exoskeleton for camera systems (Amazon 2022)

In conclusion, basic concepts are as follows:

1. Wearable
2. Hold the drill in the horizontal and overhead position
3. Achieve static load compensation at an extent of no less than 50%
4. Reduce hand and/or arm vibration
5. Be able to work with/without an external exoskeleton
6. Light-weight

2.2 Embodiment design

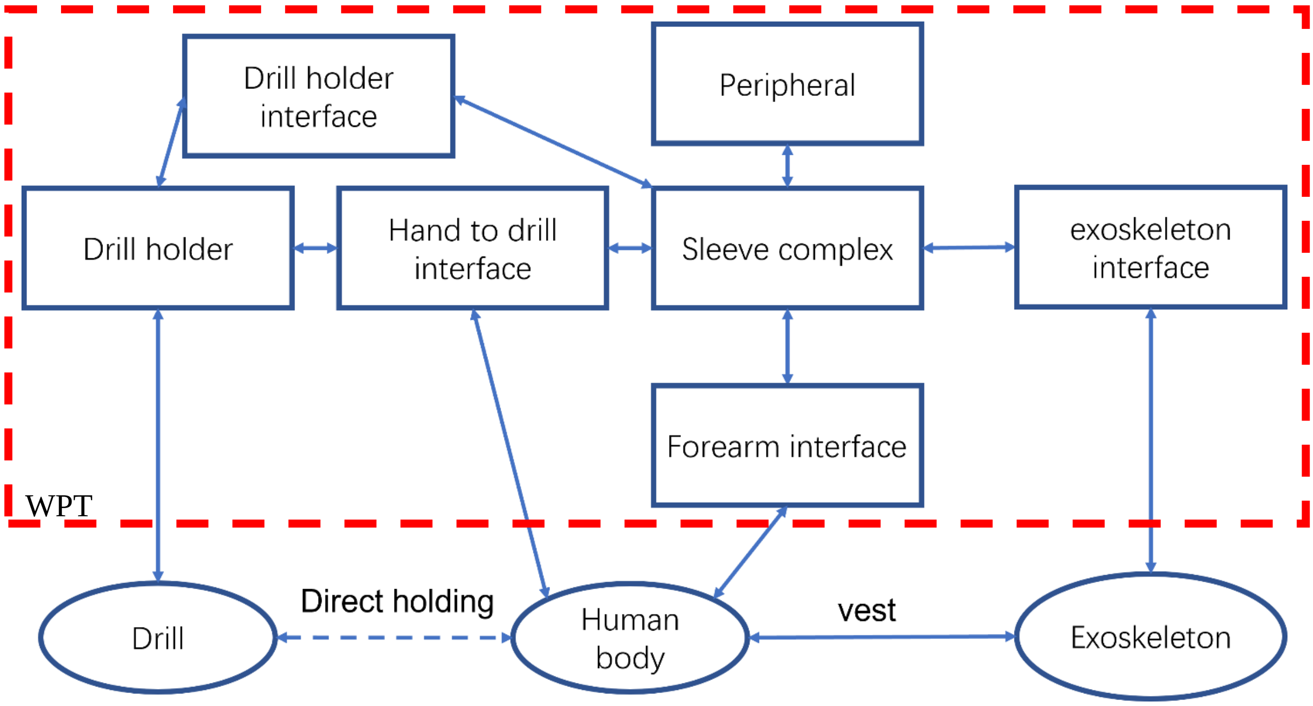
In this section, three phases of embodiment design are discussed, which are product architecture, design configuration, and preparations for further design.

2.2.1 Product architecture

According to all the concepts mentioned in the concept design, the WPT is a wearable device that firstly wraps around the forearm, secondly has one interface to the exoskeleton as well as one to the drill. Thirdly, multiple degrees of freedom must be provided to support the horizontal as well as overhead working position, and ensure comfortable use on the wrist and elbow. Fourthly, personalized expansions may be needed, so an interface to peripherals is also prepared.

In such a case, the prototype's systems can be divided into drill holder, hand-to-drill interface, WPT-to-forearm interface, WPT-to-exoskeleton interface, and peripherals.

All the subsystems are connected in *Figure 2-2*.



Attention: the drill and human body are only connected when the direct holding method is applied.

Figure 2-2: Product architecture of WPT

The functions of all essential subsystems are explained below:

The drill holder is the part that holds the testing drill in position and provides an interface to other subsystems.

Hand-to-drill interface solves the problem of how to grip or manipulate the drill.

A certain drill-holder-to-WPT interface is needed when the hand is not holding the drill directly. It supports the drill holder and connects it to the sleeve complex.

The WPT-to-forearm interface, also known as the human-machine interface or sleeve complex, is the crossroad of the overall system, connecting the various subsystems. Concerning its direct contact with the human body and its load-carrying responsibility, the sleeve complex is the most critical aspect of this wearable device.

WPT-to-exoskeleton interface is one of the main load-carrying components. This component is required to be lightweight while maintaining sufficient strength and stiffness. It provides a standard interface to a chosen exoskeleton. In addition, it has the function of enabling both horizontal and overhead working positions.

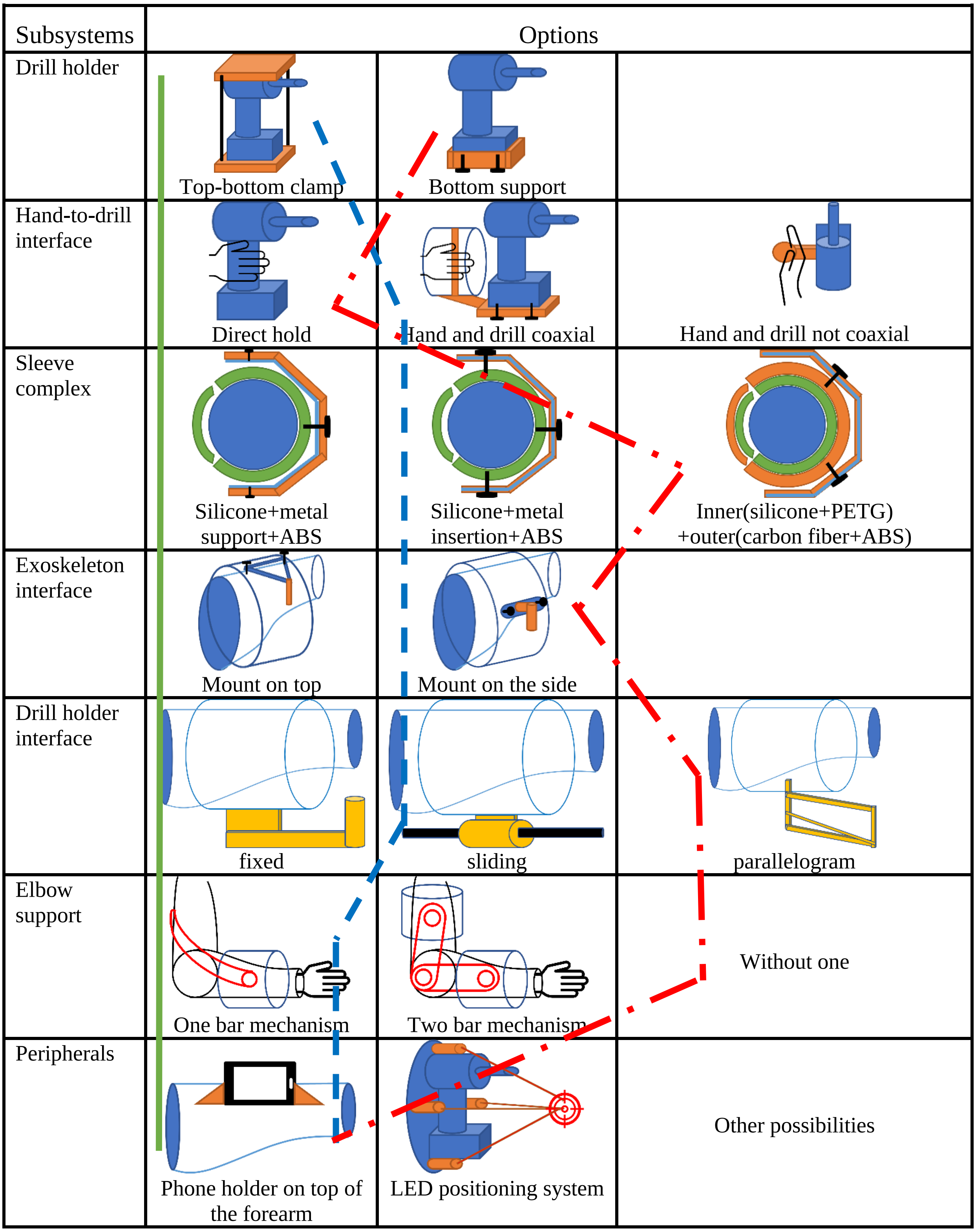
Peripherals are optional components that are made modular to adapt to customized functions. For example, if an information terminal is needed, a phone holder mounted on top of the arm would be useful. Some other peripherals that can help improve efficiency are also taken into account, the more representative ones being a lighting system, an automatic LED positioning system, and a drill-depth alarm system.

2.2.2 Design configuration

After the product architecture is determined, the exploration of different solutions is the next step. All the parallel ideas on the main functionalities mentioned in the product architecture that occur throughout the development process are concluded in the morphological chart*(Chart 2-1)* below.

Because a total of three iterations have taken place by far, three distinctive technical routes are marked. The first iteration is marked in green and solid lines. The second iteration is marked in blue and dash lines. The third iteration is marked in red and long dash-dot lines.

Chart2-1: Morphological Chart



2.2.3 Preparations for further design

Assumptions are made that the worker's torso remains motionless while using the power tool, and only the single hand holding the tool does a certain degree of translation and rotation.

Under these assumptions, we use the rotational center of the shoulder joint as an origin and establish the right-handed world coordination system (w_x, w_y, w_z). The midpoint of forearm length is used as another origin and a right-handed, arm-attached coordination system (a_x, a_y, a_z) is established, whose z-axis points at the drilling direction.

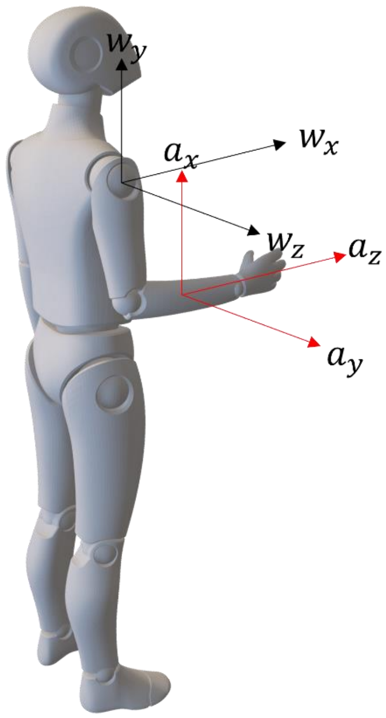


Figure 2-3: World coordination system and arm-attached coordination system

The establishment of these two coordination systems is a foundation of positioning in CAD files and facilitates future motion simulation or vibration analysis.

2.3 Detail design

In this section, three iterations of the product development process are presented.

2.3.1 Iteration 1

As the first iteration has ever been attempted, the goal was to design and build a working prototype that satisfies most of the basic requirements set out in the concept design. The requirements are confined to:

- Wearable and comfortable
- Hold the drill in the horizontal position
- Connects to drill and exoskeleton
- Static load compensation
- Be able to work with/without an external exoskeleton

The general presentation of the first generation of WPT is shown in *Figure 2-4*.

(a) *(b)*

Figure 2-4: General presentation of the 1st generation of WPT: (a) Rendered picture of the whole assembly (b)Man holding a Makita drill wearing the 1st prototype

- Sleeve complex design

For wearability and comfort, a sandwich structure has been designed, consisting of a silicone layer, a metal sheet, and an ABS housing. The sandwich*(Figure 2-5)* is used as a metaphor because, in this prototype, different materials are stacked on top of each other and wrapped around the outside of the forearm just as in the same way.

Figure 2-5: Sandwich metaphor

Crucial materials involved in the sleeve complex are introduced as follows:

Silicone, more precisely called polymerized siloxanes or polysiloxanes, is often confused with the chemical element silicon, but in fact, they are completely different substances. Silicones consisted of an inorganic silicon-oxygen backbone chain (⋯−Si−O−Si−O−Si−O−⋯) with two organic groups attached to each silicon center. Commonly, the organic groups are methyl. The materials can be cyclic or polymeric. By varying the −Si−O− chain lengths, side groups, and crosslinking, silicones can be synthesized with a wide variety of properties and compositions. *(Wikipedia 2022b)*

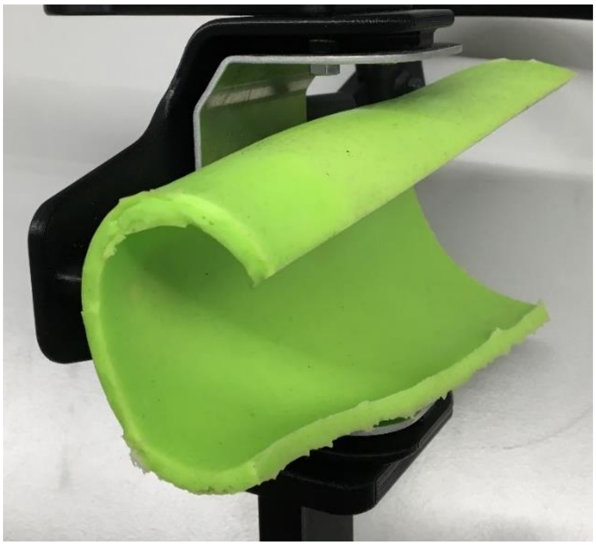
Properties of silicone, like low thermal conductivity, low toxicity, flexibility, and easy buildability, can be exploited in our design process, for it is a perfect human-tool interface suitable for laboratories. The specific applications are as follows:

First of all, direct contact between the silicone layer and the human body blocks the sharp edges of metal and plastic that may occur in the manufacturing process. In addition, a silicone layer provides reliable protection against possible shocks. Last but not least, a silicone layer proves to be a rather effective passive vibration isolation material.

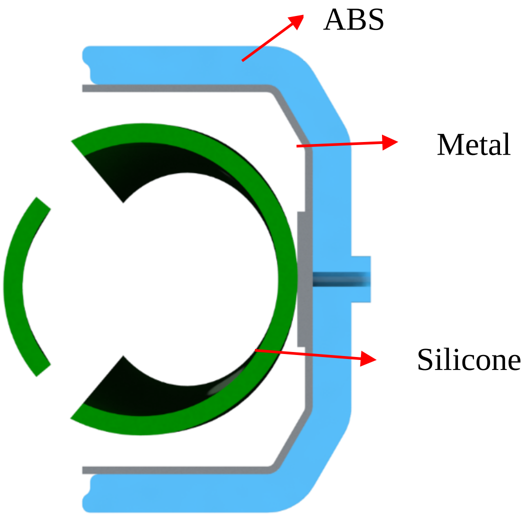
For other materials included in the sandwich structure, the metal sheet plays an important role in supporting the load and maintaining structural integrity.

The 3D-printed ABS housing as the outermost layer is helpful to keep a neat appearance and acts as an interface to other subsystems.

The whole structure is shown in *Figure 2-6*.



(a)



(b)

Figure 2-6: Sleeve sandwich of iteration1 (a) Real assembly of sleeve complex of iteration 1 (b) A cross-section of the virtual assembly of sleeve complex of iteration 1

- Elbow support design

Elbow support is also introduced so that the users can use the upper arm as support when the WPT is working alone and rest on the upper arm when it works with an exoskeleton.

Figure 2-7: Elbow support of iteration 1

- Exoskeleton interface design

For holding the drill in a horizontal position, the interface between the sleeve complex and exoskeleton has been designed to have only one degree of freedom, making it only possible to rotate on the horizontal plane.

In this iteration, this interface is constructed to be as simple as possible, as shown in *Figure 2-8*.

Figure 2-8: The interface between the sleeve complex and exoskeleton

- Drill holder interface design

For the connection between the drill and the sleeve complex as well as for static load compensation, the simplest way is to hold the two with a rigid beam. Considering the height adjustment, one screw system is added.

Figure 2-9: The connection between the drill and the sleeve complex

2.3.2 Iteration 2

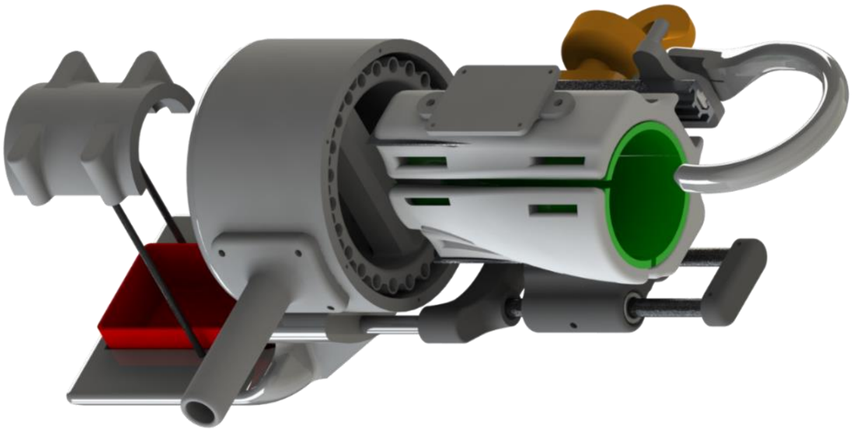
After iteration 1, the industrial design approach was introduced to our team and the design objective was further expanded to design a product whose functionalities are fulfilled as well as the looks of the product are taken into account. In the meantime, the product design stays as close as possible to all the requirements set out in the concept design phase.

The requirements are adjusted to:

- Wearable
- Hold the drill in the horizontal and overhead position
- The connection to drill slidable
- The connection to the exoskeleton rotatable
- Static load compensation
- Be able to work with/without an external exoskeleton
- Good-looking

The overall look of the second iteration of WPT is presented in *Figure 2-10*:

(a)



(b)

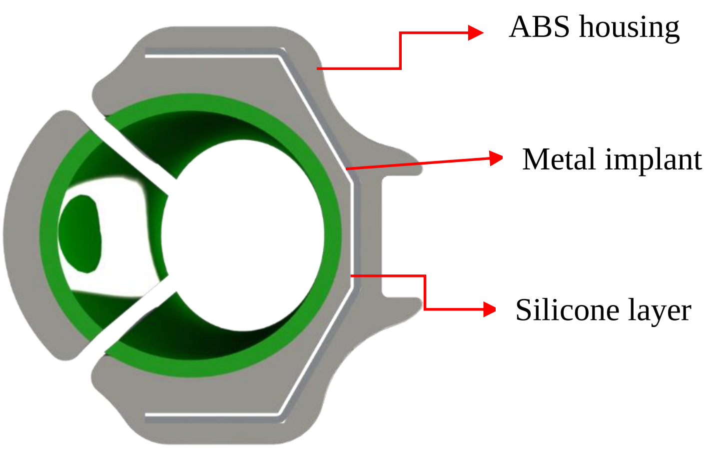
Figure 2-10: General presentation of the 2nd generation of WPT (a) Real assembly of the 2nd iteration of WPT (b)Rendered image of the virtual assembly of the 2nd iteration of WPT

- Sleeve complex design

For wearability and an appealing appearance, a new sleeve sandwich has been designed, with a silicone layer at the innermost part, and a 3D-printed ABS layer at the outermost part. A 2mm metal sheet was inserted into the ABS part. The real assembly and the cross-section of the virtual assembly are shown in *Figure 2-11*.

(a)

(b)

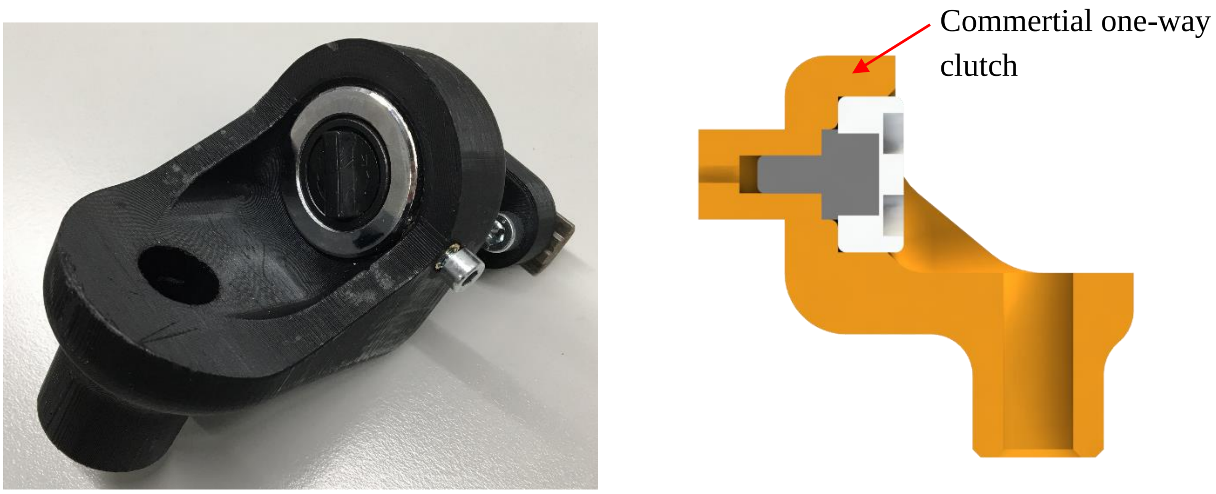


(c)

Figure 2-11: Sleeve complex of iteration 2 (a) View from the bottom of the real assembly of sleeve complex of iteration 2 (b) View from the top of the real assembly of sleeve complex of iteration2 (c) A cross-section of the virtual assembly of sleeve complex of iteration 2

- Exoskeleton interface design

For holding the drill in the horizontal and overhead position, the interface between the sleeve complex and the exoskeleton has to be of at least 2 degrees of freedom. One allows the WPT to rotate on the (a_y, a_z) plane and the other allows it to pitch upwards or downwards on the (a_x, a_z). In this case, a clutching system containing a commercially used one-way clutch has been integrated.



(a) *(b)*

Figure 2-12: Clutching system for iteration 2 (a) Real assembly of clutching system (b) A cross-section of the virtual assembly of the clutching system

- Drill holder interface design

For the connection to the drill to be slidable, a carbon-rod-based sliding system was designed in this iteration. Instead of using a static connection between the drill and the sleeve complex in iteration 1, a change to a sliding system has the following advantages:

- Adjustments along the z-axis are possible.
- The mechanism is more compact.

The disadvantages are also clear:

- The weight of the mechanism has increased.
- Adjustment along the x-axis is no longer possible.

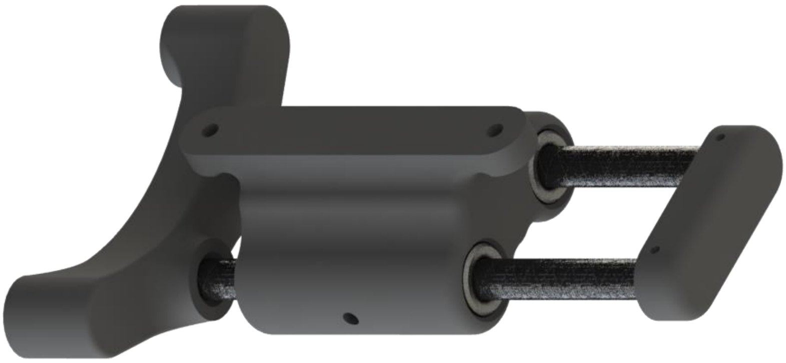


Figure 2-13: Sliding system in iteration 2

- Hand-to-drill interface design

For more comfortable use without exoskeleton support, in iteration 2 an additional structure has been designed as an interface between the hand and drill holder. With the weight of the drill itself and the additional weight of the WPT, it appears more reasonable to share the weight of the whole assembly between two hands, especially when there is no external support. Therefore, a side handle is added to the interface.

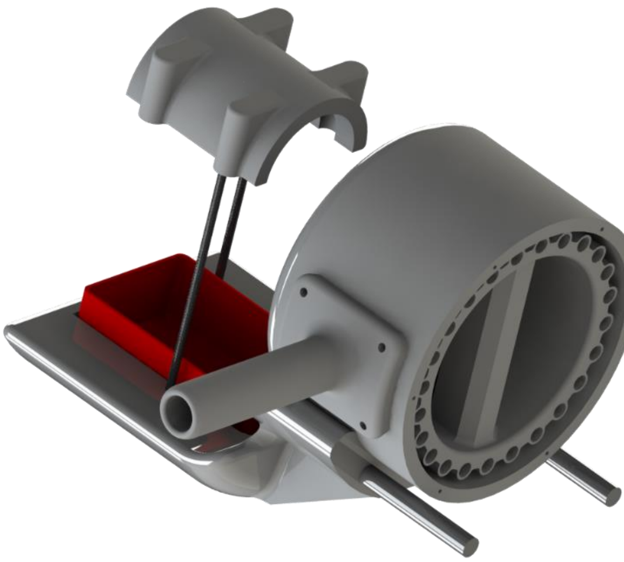


Figure 2-14: Hand-to-drill interface in iteration 2

2.3.3 Iteration 3

With the experience of the first two iterations, the purpose of the third iteration is further extended to building a working prototype that takes into account the product's appearance and is more in line with market needs. Therefore the new requirement of adaptability is included, whose aim is to adjust not only to our testing personnel invited for this project but also to the majority of potential customers.

The requirements are defined as:

- Wearable
- Hold the drill in the horizontal and overhead position
- The connection to drill slidable
- The connection to the exoskeleton rotatable
- Static load compensation
- Be able to work with/without an external exoskeleton
- Good-looking
- Adaptability
- Light-weight

The overall appearance of the third iteration of the WPT is demonstrated in *Figure 2-15*:

(a) *(b)*

Figure 2-15: Overall look of iteration 3: (a) Man holding a Markita drill wearing the 3rd iteration of the WPT (b) Rendered image of the virtual assembly of the 3rd iteration of WPT(with the drill mounted on)

- Sleeve complex design

For wearability, the technique of sleeve sandwich combining silicon, metal, and ABS parts has already been mature. However, in this iteration, for adaptability and lightweight design, the sleeve complex requires a radically renewed design.

In designing the sleeve sandwich for iteration 3, the strength and stiffness of the structure are naturally factored in, and the solution is analog to previous iterations, i.e. to embed a high-strength material into the 3D-printed ABS plastic so that the composite can be lightweight at sufficient strength. As opposed to the traditional method of acquiring supporting structure by bending aluminum sheets, we have decided to use a novel technology, 3D-printed carbon fiber, for lightweight requirements. Because 3D printing carbon fiber is extremely expensive and time-consuming, a plastic part made of high fill rate ABS material is used as a substitute for now.

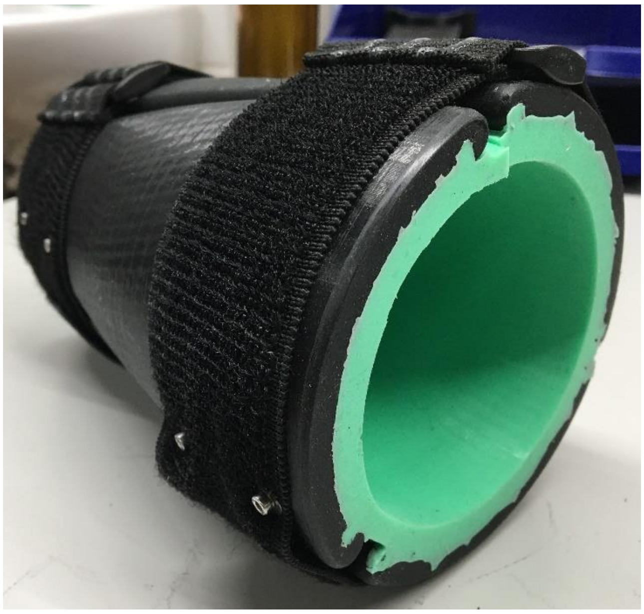
Considering adaptability to different populations, there are two obvious ways of realization. One is universality and the other is customization. Universal design is of course a fine option, as it greatly increases the interchangeability of the product among people, but it usually increases the complexity of the product structure and the difficulty of maintenance at a later stage. Customization on the other hand can drive up the cost of use for potential users and extend the production period. However, customization is an efficient way of reducing product complexity and improving product reliability. And it is helpful with post-production maintenance.

Neither of these two methods alone is good enough for this integration, so decisions have been made to combine these two in one product, taking advantage of both universality and customization. This is made possible by dividing the whole sleeve complex into the inner and the outer parts. *(Figure 2-16)*

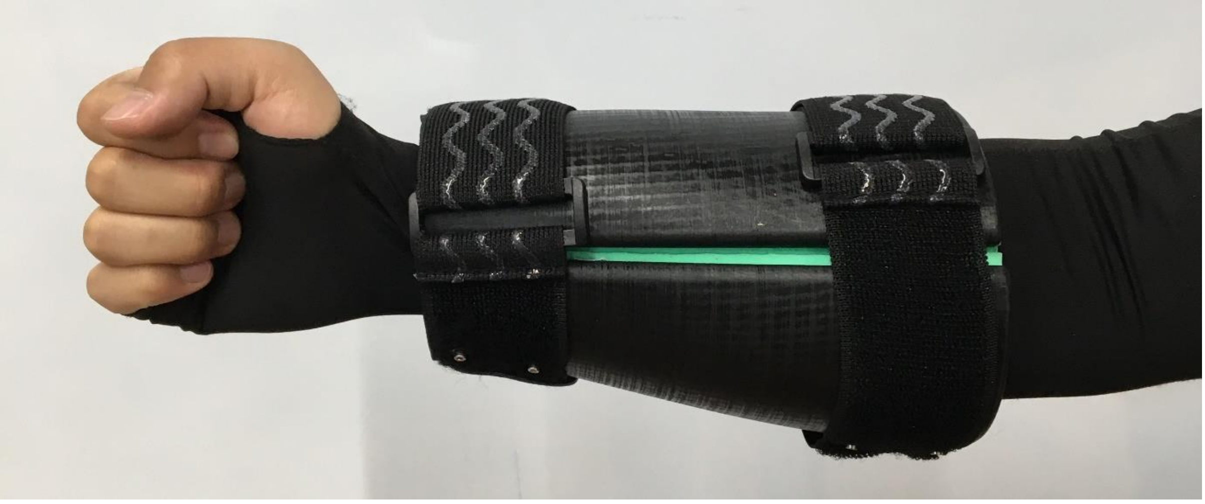
The outer part, consisting of carbon fiber implants and ABS housing, is designed to be universal, in order to accommodate a wide range of peripherals, different loads, and various types of exoskeletons for external support.

In the meantime, the inner part, made up of a silicon layer, PETG plastic as housing, and a strapping system for wearing, is produced on a customized basis according to the varying mapping data collected from the user.

Putting the inner and outer parts together brings the whole sleeve complex, simultaneously universal for the instrumental factor and unique for the human factor. *(Figure 2-17)*



(a) *(b)*



(c)

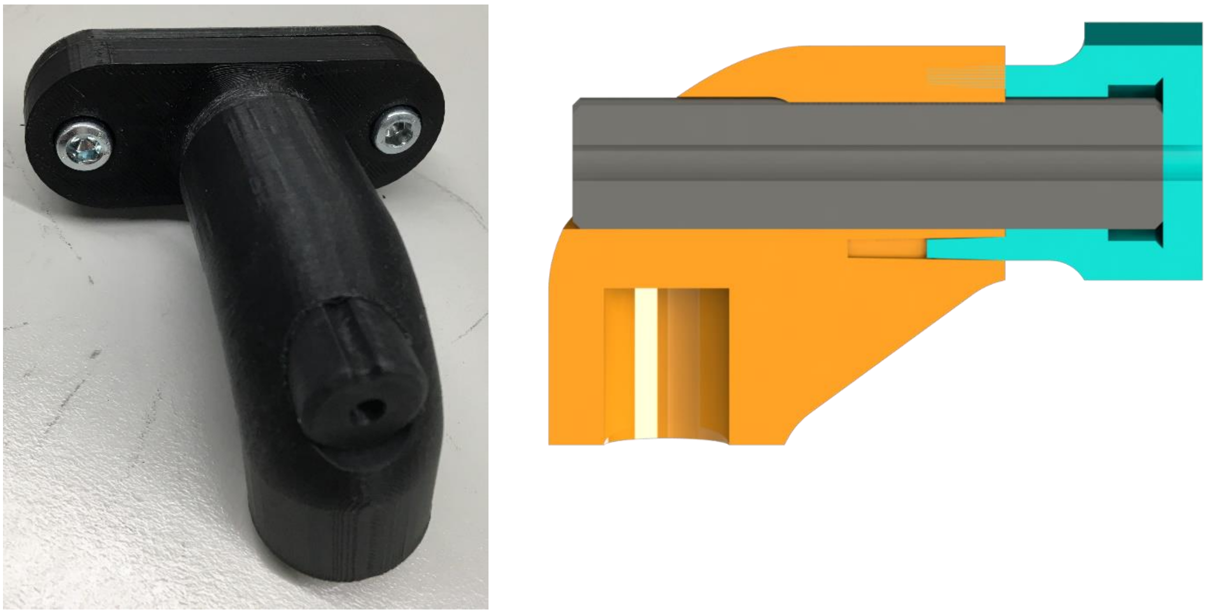
Figure 2-16:Inner and outer part of sleeve complex of iteration 3 (a)Inner part (b)Outer part (c)Man wearing the inner part of the sleeve complex

(a) *(b)*

Figure 2-17: Assembly of sleeve complex of iteration 3 (a) Real assembly of sleeve complex (b) a cross-section of the virtual assembly of the sleeve complex of iteration 3

- Exoskeleton interface design

For holding the drill in the horizontal and overhead position, a new design of clutching system has been designed in replacement of the former one-way clutch system, for lacks reliability. The new system takes inspiration from the widely-used dog clutch and has been modified to match the application environment here.



(a) *(b)*

Figure 2-18: Dog clutch of iteration 3 (a) Real assembly of dog clutch system (b)A cross-section of dog clutch assembly

- Drill holder interface design

For static load compensation, the rigid structure concept from the first two iterations has been abandoned. Instead, a parallelogram mechanism based on extension springs is designed.

The parallelogram mechanism shown in *Figure 2-19*, called the standard parallelogram, is actuated by an extension coil spring fixed diagonally within the parallelogram between points A and B. *(Altenburger et al. 2016, S.2)* An external load acts on the right bar in the vertical direction marked with force G. Bar a's angular deviation from the horizontal plane is denoted as φ. According to vector addition, the resulting tension and compression force in the bars a,b and c are related to their geometric length, i.e.

$$\frac{F_a}{a} = \frac{F_b}{b} = \frac{F_c}{c} \tag{2-1}$$

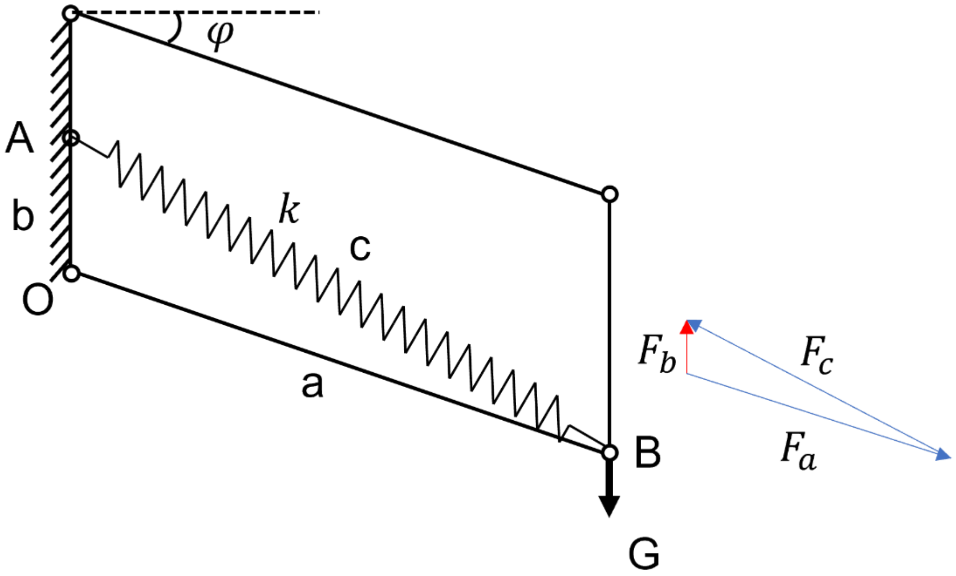


Figure 2-19: Force analysis of a standard parallelogram mechanism using tension spring

In an equilibrium state, the force F_b corresponds to the external load, in this case, G.

$$F_b = -G \tag{2-2}$$

And the force F_c corresponds to the restoring force of the tension spring. Assuming the spring is ideal(zero free length l_0, no pretension F_0), the force should be:

$$F_c = F_{spring} = kc \tag{2-3}$$

Where k is the spring constant. Under this assumption, the lifting force of the parallelogram mechanism is F_b:

$$F_b = \frac{b}{c} F_{spring} = \frac{b}{c} kc = kb = const \tag{2-4}$$

For an ideal spring, the lifting force F_b is independent of the spring length c and the angular deviation φ. This means no external force or torque is needed to balance the weight of the mechanism within its workspace.

Yet, springs in real life are non-ideal. Normally, the restoring force of a tension spring can be expressed in *Formula 2-3*:

$$F'_{spring} = k(c - l_0 - x_0) + F_0 \tag{2-5}$$

Where x_0 is the installation length of the spring, l_0 is the free length of the spring, and F_0 is the pretension of the spring.

Ignoring the friction of the rotating pairs and the weight of the mechanism itself, the lifting force F_b can be expressed as:

$$F_b = \frac{b}{c} F'_{spring} = \frac{b}{c} [k(c - l_0 - x_0) + F_0] \tag{2-6}$$

Where the variable c can be substituted with the geometrical condition:

$$c = \sqrt{a^2 + b^2 - 2absin(\varphi)} \tag{2-7}$$

In our case, due to confined design space, the parallelogram mechanism is rotated to be 100° to the horizontal plane, as shown in *Figure 2-20*. Therefore, a correction has to be made by applying the following formula.

$$F'_b = F_b \times sin(\theta) = G \tag{2-8}$$

Where $\theta = 100°$.

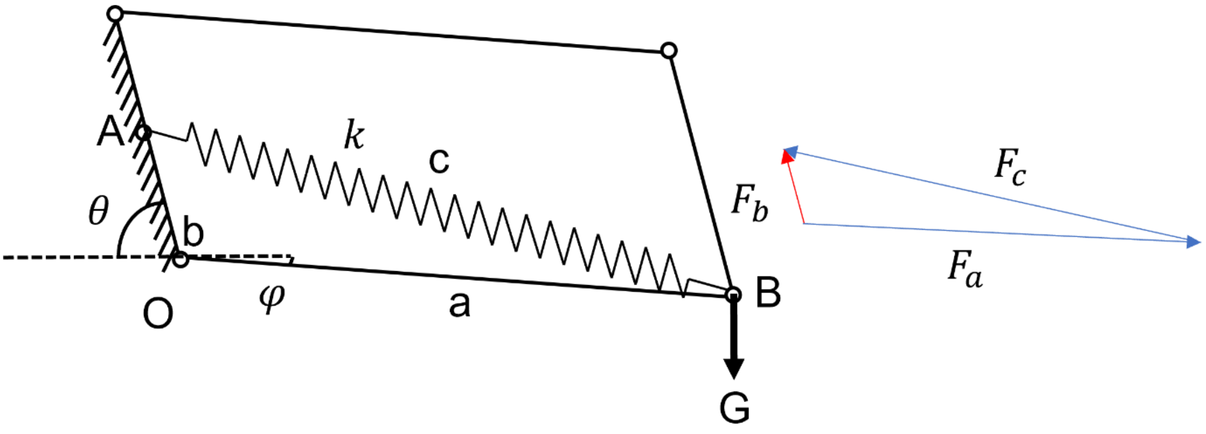


Figure 2-20: Force analysis of the parallelogram mechanism integrated into the design

The real assembly of the parallelogram is shown in *Figure 2-21*.

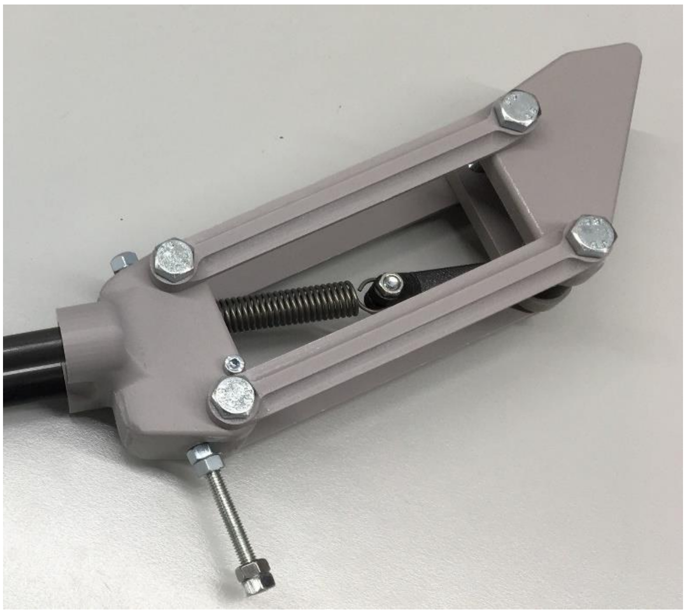


Figure 2-21:Real assembly of the parallelogram mechanism in iteration 3

2.4 Tests & Experiments

Tests and experiments are specifically done for comparing the working status of the real parallelogram mechanism in the WPT prototype to theoretical calculations.

2.4.1 Testing and polynomial fitting for chosen tension spring

The tension spring used to assemble the parallelogram mechanism is not provided with corresponding technical parameters. Thus the first step is to perform a tension test and use polynomial fitting to determine the spring constant k and pretension F_0.

As is shown in *Figure 2-22*, the original data of the tension test is denoted as stars*(*)*. The first three data points lie in the non-linear working area. The reason for this starting nonlinearity is unknown.

Excluding these three non-linear data points, the rest of the data points fit the properties of a linear spring very well. After performing a first-order polynomial fit *(Matlab function polyfit)*, the resulting line can be expressed as $y = 1.1230x + 10.5981,$ therefore, the spring constant $k = 1.1230$ equals the line slope, and the pretension force $F_0 = 10.5981$ equals the bias.

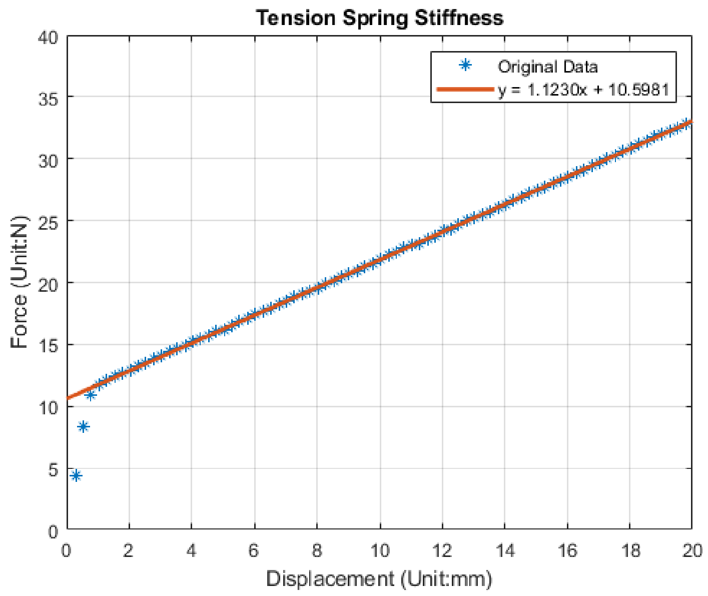


Figure 2-22: Tension test on the spring

2.4.2 Test bench setup and preparation for the test

According to *Formula 2-6*, the resulting force F_b is related to a, b, c, k, l_0, F_0, φ. Measures can be made on both CAD files and the real prototype. The results are shown in *Formula 2-9*:

$$\begin{cases} a = 130m\,m \\ b = \ 43.4\,mm \\ k = 1.1230\ N/mm \\ l_0 = 45\,mm \\ F_0 = 10.5981N \\ \varphi \in [-\frac{\pi}{3}, \frac{\pi}{10}] \end{cases} \tag{2-9}$$

Where the variable φ needs to be translated into the travel of the endpoint of the parallelogram in order to meet the unit used in the test.

And the setup of the test bench for the force-displacement test of the parallelogram mechanism is shown in *Figure 2-23*.

The temporary fixture is constructed from aluminum profiles. The parallelogram for testing is clamped to the upper surface of the fixture by a plastic plate. During the test, the intender of the test bench is always in close contact with the surface originally designed to interfacing with the drill holder.

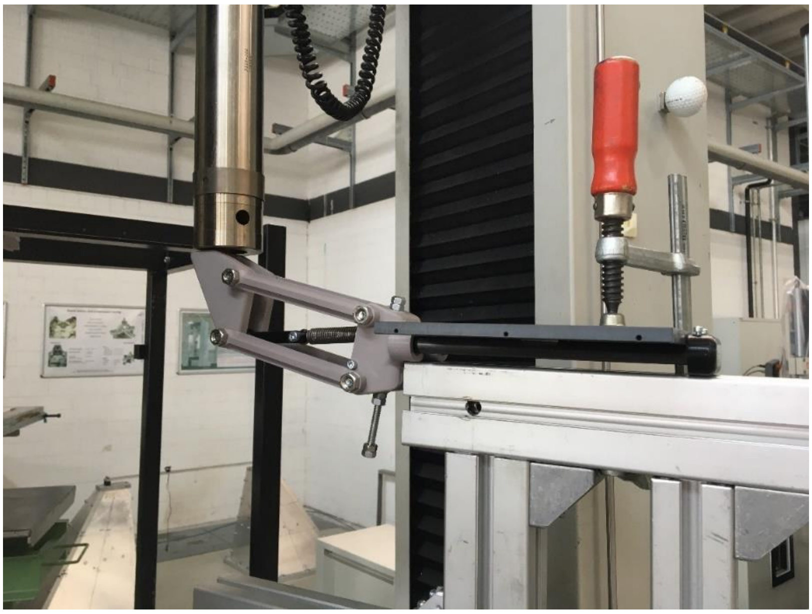


Figure 2-23: Test bench for the force-displacement test of the parallelogram mechanism

2.4.3 Interpretation of the test result

The test result of the real prototype is demonstrated in *Figures 2-24* in the form of a force-displacement curve. When pressing down, the working point follows the blue line, and on return travel, it follows the red line. And the theoretical calculation is marked in yellow.

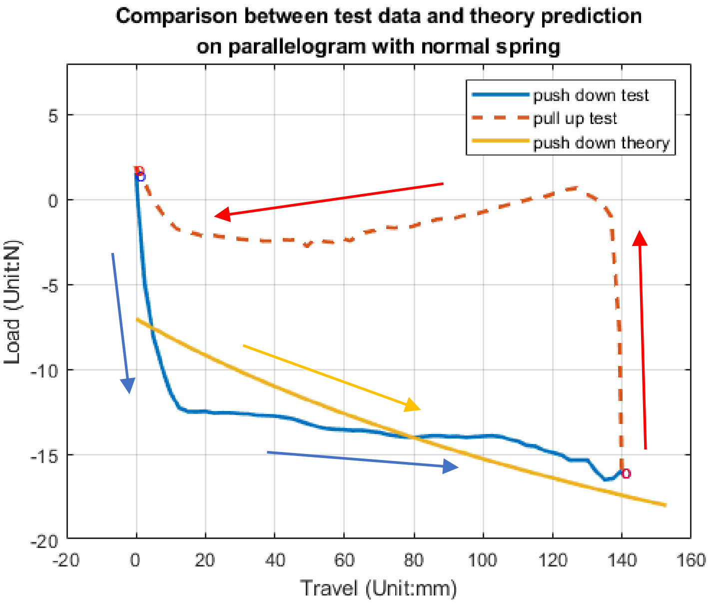


Figure 2-24: Comparison between theoretical calculation and tests of the force-displacement curve

It is clear that within a cycle, the force-displacement curve possesses the characteristics of a hysteresis curve. There is a high probability that the frictional force in the opposite direction of motion acts as a driving force when pressing down and as resistance when rebounding. And the reason why the actual support force is almost zero during the rebound stroke is expected to be that the absolute value of the sliding friction force and the theoretical support force are essentially equal.

Given that the working area of the parallelogram mechanism is located in the push-down stroke, it is our main focus to check the difference between the theoretical result(yellow curve) and the test result(blue curve) in this area.

The theoretical calculation based on friction-free assumption results in a monotonically decreasing concave function ranging from -7N to -17N. In terms of trend, the actual measurement is also a monotonically decreasing concave function, but with a clear inflection point $(12.4866\ \mathrm{mm}, -12.2754\ \mathrm{N})$. Before the inflection point, the absolute value of the support force rises rapidly. And after the inflection point, the support force flattens out and stabilizes around -15N. This interval after the inflection point can be defined as the working area of the mechanism.

In the working area of the parallelogram mechanism, the supporting force is between 12N and 15N. And the Markita drill for the test run weights 1.6kg. That means the rate of static load compensation using this chosen spring in the working interval is between 75% and 93.75%. In addition to that, the supporting force interval from the theoretical calculation and the actual measurement overlap in the most corresponding area.

In conclusion, there is a satisfactory match between the experimental results and the theoretical calculations, and regarding the requirements originally set for static load compensation, a 75% to 93% static load compensation rate is within the limits.

3 Result & Discussion

In this project, attempts have been made to approximate the users' needs step by step through multiple iterations of the general concept WPT. The manufacturing capabilities of the lab are also challenged. The evaluation of the different products under three iterations is as follows:

- Iteration 1:

The total structural weight of iteration 1 is 0.8kg. Wearing alone does not put uncomfortable pressure on the upper limb joints. It is believed to be the maximum weight for stand-alone usage of WPT.

Due to the only degree of freedom available on the exoskeleton interface, this iteration can only function in the horizontal working position.

The sleeve complex design is flawed because firstly, the innermost silicone layer has no fixture point to any housing, making it deformable during work. And secondly, the strapping system involved in this iteration is not convenient for putting on and taking off.

The static load compensation is 100% due to the rigid connection between the sleeve complex and the drill.

- Iteration 2:

The total structural weight of iteration 2 is 1.4 kg. It is the most weighted iteration of the three, mostly because an additional hand-to-drill interface is introduced. Operation alone with only one hand can cause fatigue quickly. However, if two hands are involved or an exoskeleton is attached, the operation is smooth.

Thanks to the clutching system composed of a commercially used one-way clutch, the overhead working position is included.

The biggest drawback of this iteration is its compatibility. On account of the tight design of all the rigid parts, this iteration is only wearable to a small range of people.

Also, because of the metal insertion idea in the sleeve complex design, it is proved to be difficult to produce in a laboratory environment with no accurate metal bending technique available.

- Iteration 3:

The total structural weight of iteration 3 is 1.2 kg. Operation alone with one hand is the only option without an exoskeleton connection and unpleasant pressure on upper limb joints especially the shoulder joint is discovered. In an overhead working position, this unwanted pressure is tolerable due to the structural support of the human body. Yet, in a horizontal working position, this unpleasant pressure is unbearable.

The design of the sleeve complex of this iteration is an advantage, for the successful combination of a customized inner part and a universally designed outer part. Thanks to the parametric design approach, the lab can reproduce a personalized inner sleeve part rapidly given the forearm measurement parameters. However, the current method of connecting the inner part and the outer part is to screw them together using bolts. A more efficient way of positioning and locking mechanism acting as an interface between the inner and the outer part is yet to be found.

Replacing the rigid supporting structure with a parallelogram mechanism is also a brand new attempt in this iteration. The parallelogram mechanism is believed to have the ability to dampen the vibration transmission to the forearm to a certain extent. With 75% to 93% of the static load compensation rate, a compromise has been made between vibration control and static load compensation. How effective this design compromise is will need to be assessed through further tests and experiments.

4 Conclusion & Outlook

In this section, conclusions on the product development process are drawn. And future work that can be advanced will be discussed in the outlook.

4.1 Conclusion

During the six months of the product development process, firstly the problem was defined to be the prevention and control of MSDs *(especially shoulder arthritis and vibration white finger)* with engineering control methods. Secondly, construction workers using power drills with strong vibration in horizontal and overhead working positions are selected as usage scenarios. Thirdly, designing a wearable, light-weight device interfacing the human arm and the drill, capable of static load compensation and vibration reduction, is the main technical means.

Although most of the requirements put forward in the conceptual design stage have been met, the overall appearance can be further optimized, many components can be further reduced in weight, and the convenience and comfort of wearing can be improved.

4.2 Outlook

4.2.1 Implementation of an air spring

There is a potential requirement that the testing drill mounting on the drill holder should be replaceable. The current Makita test drill weighs only 1.6kg, asking for the supporting force F_b provided by the parallelogram mechanism no more than 16 N. When heavier drills are applied, as shown in *Figure 1-1(a) or (c),* the supporting force generated from the current spring will be insufficient. Solutions are foreseeable, one being replacing a tension spring with a higher spring constant k, the other being using an entirely different type of spring.

The former solution is spontaneous yet it has its drawbacks. Spiral springs with a higher k tend to have a shorter free length and/or a larger coil diameter. Either of these two factors may lead to the irreplaceability of the parallelogram mechanism design. This means, that as soon as the spring needs to be replaced, the overall design of the mechanism must be changed at the same time. It is unacceptable for practical application.

The latter solution is feasible when gas springs are implemented. A gas spring is a type of spring that, unlike a typical mechanical spring that relies on elastic deformation, uses compressed gas contained within an enclosed cylinder sealed by a sliding piston to pneumatically store potential energy and withstand the external force applied parallel to the direction of the piston shaft. *(Wikipedia 2022a)*

A series of gas springs can provide different restoring forces within the same frame size. Therefore, no major modification of the mechanism is required due to the replacement of a different spring.

Air springs usually possess a relatively low spring constant k. The restoring force F_C of an ideal air spring is considered to be constant. Non-ideal ones have a certain degree of nonlinearity that can be seen in *Figure 4-1*.

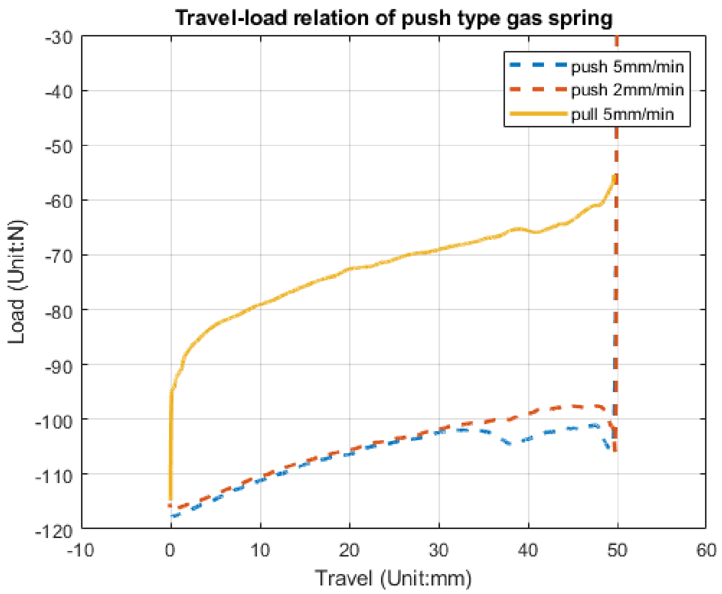


Figure 4-1: Force-displacement curve of one gas spring marked with 40N

When it is implemented into the parallelogram mechanism, the force analysis is shown in *Figure 4-2*.

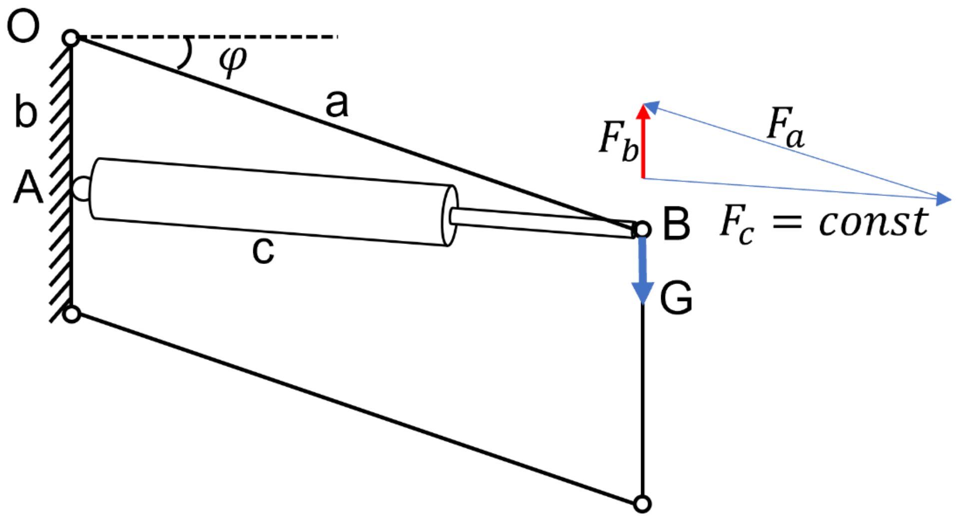


Figure 4-2:Force analysis of parallelogram with gas spring

The supporting force F_b is only related to the variable φ, as is shown in *Formula 4-1 and 4-2*.

$$F_b = \frac{b}{c} F_c \tag{4-1}$$

Where variable c can be replaced by geometrical conditions:

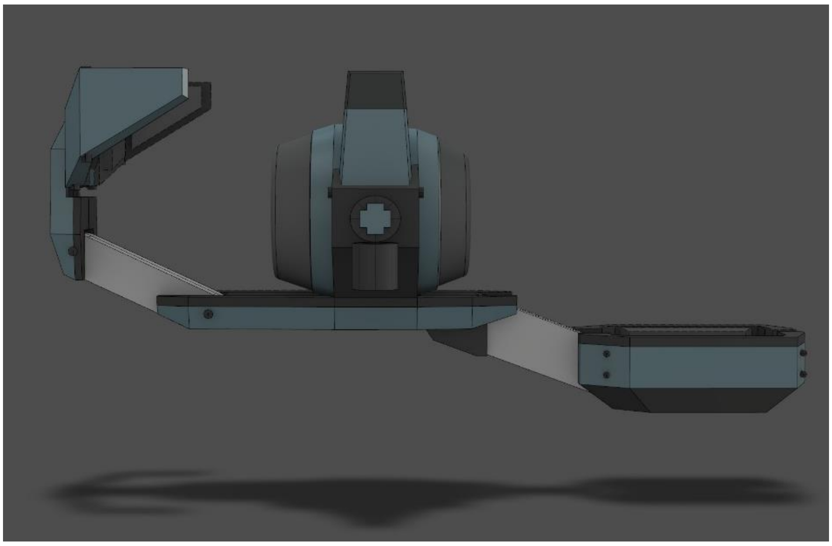
$$c = \sqrt{a^2 + b^2 - 2absin(\varphi)} \tag{4-2}$$

Further prototyping and testing are required to check the concept of implementing an air spring into the parallelogram mechanism.

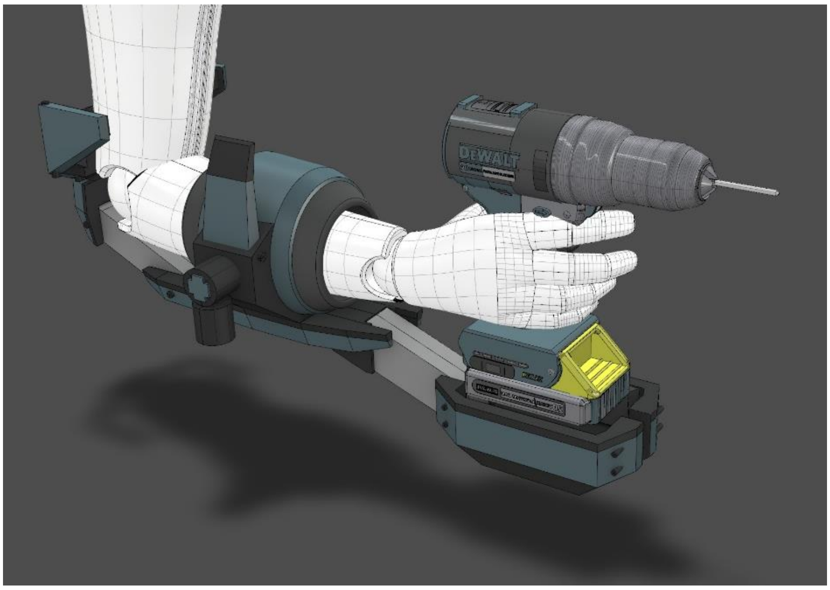
4.2.2 Optimization of overall appearance

The concept of "design first, engineering next" will dominate the advancement of the coming iterations of the project. For a more appealing appearance, a professional industrial designer was brought into the team. The files for the exterior surface will be first given by the industrial designer through analysis of user requirements and conceptual design. After that, the mechanical engineers will fill in the cavity underneath the surfaces with functional structures and mechanisms.

A new, more industrial look of the product provided by our industrial designer is demonstrated in *Figure 4-3*.



(a)



(b)

Figure 4-3: Surface design from the industrial designer (a) Side view of the overall appearance of the assembly without a drill (b) Top view of the assembly with a human wearing it and a drill mounted on it.

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