Wrist support in construction and industry work related repetitive drilling tasks.

by

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ABSTRACT

Construction and industrial workers are at high risk for work-related musculoskeletal disorders, often caused by repetitive tasks and lifting heavy loads. To reduce these work-related musculoskeletal disorders, guidelines on human strength capabilities should be followed to help mitigate injuries by reducing muscle overloading. Current solutions focus on rehabilitation and are often focused on the shoulder, elbow, and fingers, leaving the wrist vulnerable. In work-related injuries, the wrist is one of the most commonly injured body parts and is associated with high cost; both medical costs and cost due to productivity, as the median absence of work is 13 days. Injuries can be the result of bone impact forces, but more commonly muscle tissue and central nervous system damage resulting from repetitive tasks. Research shows that injuries are most common at workstations with frequent wrist deviation. Therefore, the goal of this paper is to design an orthosis to support employees in construction or industry work when working with a drill.

For the orthosis to be accepted by the users it has to be easy to use and should not limit freedom of movement. A force analysis of the wrist when holding the drill, and when using the drill against a vertical wall indicates that both the ulnar deviation and the radial deviation must be supported. To clarify which requirements are a basic necessity for the orthosis to be functional and which can be scored on functionality, they are divided into product requirements and user requirements, respectively.

Five concepts are presented to help support both the ulnar deviation and the radial deviation. Three of them are passive solutions, the other two are active. A prototype of all concepts is made and they are scored following the User Requirements utilizing a Harris Profile. During testing it is clear that the ulnar deviation support has little to no impact on the experienced muscle force. Therefore, this requirement is ignored and the orthosis ar scored with the other requirements. Both the concept using Bowden cables and the Support Arm scored well. Since the Support Arm is less complex and functional for the purpose of this research, the Support Arm is further developed.

A force analysis confirmed that the Support Arm can assist in lifting the drill by generating a configurable support force, adjustable via the spring constant or position of the attachment point. Testing the orthosis indicated that the forearm is not in line with the drill, as was expected, reducing the force on the drill. To resolve this, the attachment points of the spring and beam are angled 20 degrees to counteract the angle of the forearm compared to the drill.

The calculation in this paper are simplified, further analysis is needed to determine the effects excluded in this paper. The prototype of the orthosis should also be tested using EMG and a musculoskeletal model. This can give an indication on the effect of the orthosis on muscle activation an muscle force. More improvements of the orthosis are needed to improve user comfort and increase the force transfer. The Support Arm functions only to help lift an object. For more general wrist support and with further research, the Bowden Cable concept is promising. While more complex, the concept can help with dynamic forces to assist to the wrist movements.

In conclusion, the Support Arm orthosis effectively reduces the experienced muscle load during radial deviation when a drill is being lifted. The supporting force of the orthosis can be easily modified depending on the task. For the goal of this research, to support employees in construction and industry work when working with a drill, the Support Arm is a functional solution that can decrease the necessary muscle force and, in doing so, also decrease the bone contact forces in the wrist.

1. INTRODUCTION

Approximately 23 percent of work-related musculoskeletal disorders are reported by manufacturing industries [1]. This includes only injuries associated with exposure to risk factors and no disorders caused by falls or other accidents. This makes sense as, during construction and industry work, a lot of lifting and pushing is required, as well as driving, screwing, hammering, and writing [2]. Workers walk around with tools in their hands and heavy parts need to be carried and placed in different locations. During these activities, the upper body must withstand these changing heavy loads. These activities can contribute to the development of injuries if the load is too heavy or the work is repetitive. This can happen through 3 primary pathways: reorganization of central nervous tissue can be the result from repetitive tasks, tissue injury and compression can be caused by repetitive movements and/or forceful movements, and lastly, tissue reorganization as a result from repetitive loading can decrease the biomechanical tolerance [1]. These Cumulative Trauma Disorders can develop when a task that requires excessive force is repeated in intervals of less than 30 seconds [3, 4]. To reduce injuries in construction and industry work, guidelines based on human strength capabilities are necessary. This can help control injuries by reducing muscle overloading [3].

Currently, there are already solutions to support the human musculoskeletal system. These exoskeletons can be used to extend human performance [5, 6]. For example, the Bowden-cable-based series elastic actuation system proposed in [5] is a system to assist leg movement. Other exoskeletons, such as the ExoActive from Festool [7], can transfer loads from the arm to the torso to relieve the load on the shoulder, Figure 1. The SCRIPT passive orthosis assists in the extension of the fingers and wrist [8]. Both the Exxovantage [9] and Sabeoflex [10] have a similar mechanism to extend the fingers and the wrist. In [11], an active wrist orthosis is proposed to assist the dart-trowing motion. Other wrist exoskeletons based on Bowden cables are the Assistive Soft Wrist Exosuit presented in [6] and the Elbow-Wrist Exosuit presented in [12]. The former is designed to assist the flexion movement in the wrist, the latter supports both flexion and extension in the wrist, as well as the elbow. An other exoskeleton that supports both flexion and extension in the wrist is the eWrist [13]. Instead of Bowden cables, this design uses a DC motor in combination with gears to support the wrist. Lastly, the Carbon Hand [14] is designed to increase the grip strength of the user when handling heavy objects.

Fig. 1: Exo-Active by Festool in use when drilling [7]. In the image the exoskeleton is seen as it supports the shoulder and elbow but not the wrist.

Most of the mentioned devices are intended for rehabilitation and not to actively assist healthy users. Furthermore, the wrist is often overlooked in such devices, as most modern exoskeletons focus on the elbow and shoulder [6], or only on the hand [13]. This is also visible in the review of shoulder-elbow-wrist supporting exoskeletons by [15]. The exoskeleton in Figure 1, the ExoActive, shows this problem. The user holds a drill above head height while wearing the exoskeleton. The shoulder is supported and even the elbow might have some support to lean on, but the wrist has to carry the weight of the drill and keep it in position without external support.

In work-related injuries, the wrist, hand, and fingers are the most commonly injured body parts [16]. Of all work-related musculoskeletal disorders, wrist injuries are also associated with high costs in the working population, especially in construction and industry work [17]. Partially due to medical costs, but also due to productivity costs, with a median absence of 13 days [1, 17]. Repeated injury can lead to more severe disorders that might require an operation. Resulting in even longer absences of more than 130 days or even unemployment due to permanent disability [16, 18].

During work activities, all movements in the wrist are required, as presented in Figure 2. Most notably flexion, extension, radial deviation, and ulnar deviation [15]. Although it is not exactly a movement in the wrist, but rather in the forearm, pro- and supination are also needed to function [19, 20]. Rotation of the forearm also affects force transfer through the wrist joint. The majority of the force is then transferred to the radius. More of the force can shift to the ulna during pronation or some hand grips [21, 22, 23]. Because of this the wrist has both bone contact forces and muscle forces that can result in injuries.

Injuries resulting from bone contact forces are often the result of a longer ulna. However, people with a neutral ulna length can still experience this Ulnar Impaction Syndrome as it can be caused by dynamic impact of the ulna [23]. More common are injuries in muscle tissue and central nervous tissue resulting from repetitive tasks. Because wrist joints are stabilized by ligaments; loading the wrist

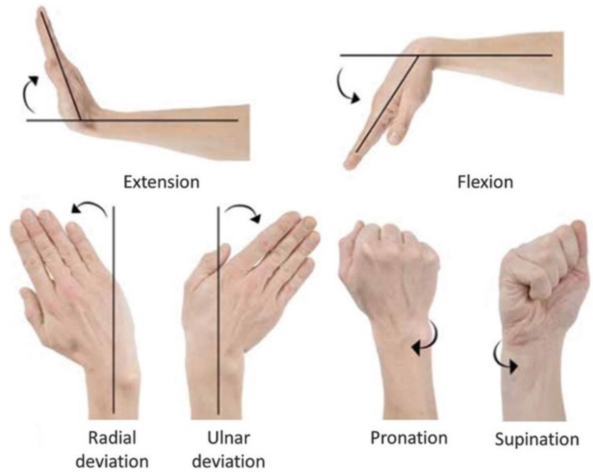

Fig. 2: The three movement axis in the wrist: extension / flexion, radial deviation / ulnar deviation and pronation / supination. [20]

at different angles can have an effect on different areas of the wrist [21]. Therefore, injuries can vary depending on the tasks performed. The loading of the wrist during repetitive tasks can cause inflammation and thickening of the active tendons over time. Alternatively, repeated or acute injuries can result in a rupture [24].

Research by [25] shows that in workstations with frequent wrist complaints, deviation occurs more frequently and in a wider range than in workstations with a low frequency of wrist complaints. This indicates that ulnar deviation can be a risk factor for wrist injuries. Although focusing on tennis players, [24] also discusses impairments on the ulnar and radial side of the wrist. For this reason, support mechanisms should focus on the possibility of supporting ulnar and radial deviation to prevent these injuries.

Due to the current lack of assistive wrist exoskeletons for work environments, this paper will focus on the design of a wrist orthosis to support radial and ulnar deviation. The device has to support physically demanding tasks, lifting objects from around 3 kg, as this can already reduce the risk of work-related musculoskeletal disorders [12]. For this reason, this paper will focus on the work performed with a drill to highlight the impact of the orthosis on muscle load during radial and ulnar deviation.

The goal of this paper is to go through the process of designing an orthosis to support deviation in the wrist and to propose a prototype solution to support employees in construction or industry work when working with a drill of around 3 kg.

2. PROBLEM DEFINITION AND REQUIREMENTS

As mentioned in Section 1, injuries can occur due to bone contact forces or due to muscle strain. When muscles contract, it creates a moment in the joint, which is needed to apply force with the hand. This high muscle force in combination with a small moment arm also results in a high bone contact force. In the wrist, muscle injury is the most common in the muscles for radio and ulnar deviation. For the purpose of this paper only the wrist is considered as the elbow and shoulder already have several tools to reduce muscle load.

2.1. Current Solutions

Current wrist support orthoses on the market focus on rehabilitation or support of the hand and wrist by fixating the movement axis in the wrist. However, these solutions are often not applicable when working with a drill.

For example, the SaeboFlex and SaeboGlove both focus on rehabilitation by limiting the movement in the wrist by fixating it using a splint. They focus on training hand strength with the use of springs to extend the fingers 3. These passive devices, always active and without electronics, can support activities where a fixated wrist and extension in the fingers is needed. For the varied movements in construction or factory work, these orthosis limit the body too much to be useful. [10]

Fig. 3: Two hand orthosis from Sabeo. *On the left*: the SabeoFlex, intended to help grasp objects after neurological impairments. *On the right*: the SabeoGlove, intended for hand rehabilitation. [10]

The devices from Exxovantage can fixate the movement in the wrist in different increments or limit the Range of Motion (RoM). This should support the wrist when handling tools or equipment 4. However, as this limits the RoM of the wrist, handling tools and equipment can become complicated in some situations. [9]

Fig. 4: Two orthosis by Exxovantage intended to increase support during load and tool handling. *On the left*: the Slim Wrist Band. It applies pressure to the tendons to decrease the RoM and prevent overloading. *On the right*: the Exxovantage Daya Wrist Exoskeleton. It fixates the wrist to reduce pressure. [9]

2.2. User Acceptance

In addition to the fact that the orthosis must be functional, it must be comfortable to use [8]. If it is complicated to put on or limits too much movement, user acceptance will be low, as it is easier to quickly drill something without it [13]. The orthosis should therefore be portable and not limited to one location where it must be donned and doffed for each use [6]. To not limit the user's movement during other tasks, the orthosis should minimally limit the movement axis and RoM in the joints. In the forearm, pronation and supination should not be affected as these movements play an important role in most activities [19]. In the wrist, the orthosis should not have a negative impact on flexion and extension movement and it should work within the RoM of the radial and ulnar deviation axis. This is within 20 degrees of radial deviation and 40 degrees of ulnar deviation [2, 26].

To understand whether this full RoM is used when working with a drill, a quick analysis is performed using Kinovea [27]. Pictures are taken when drilling above the head, at chest height and at hip height, as you can see in Figure 6. This results in wrist angles of 30 degrees ulnar deviation and 5 degrees radial deviation, respectively. To function in these scenarios, the orthosis should be able to work in this range of motion of 30 degrees of ulnar deviation and 5 degrees of radial deviation [2].

2.3. Force Analysis

As this paper focuses on designing an orthosis to support construction and industry work with a drill, there are two scenarios to define: lifting the drill, and using the drill by pushing it against a surface. Figure 5 depicts the two scenarios and the corresponding Free Body Diagram (FBD).

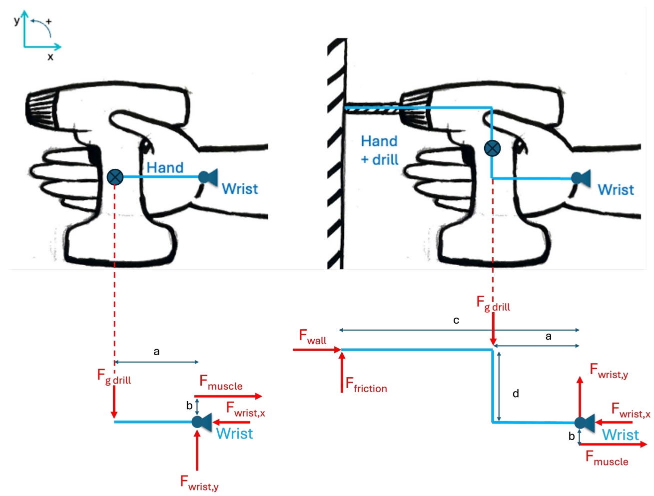

Fig. 5: *Left*: FBD of the hand with the weight of the drill. The wrist is a locked point where only rotation is possible. The hand is depicted as a weightless beam with the gravitational force at the end. The center of gravity on the top image is connected to the FBD below to indicate the location of the gravitational force.
Right: FBD of the hand and drill when drilling in a vertical wall. The hand and drill are depicted as one connected structure. The center of gravity on the top image is connected to the FBD below, where the vertical change of the forces is placed, to indicate the location of the gravitational force.

When lifting the drill, the user has to counteract the gravitational force on the drill, the body has to create a clockwise moment in the wrist to counteract this force, radial deviation. This is depicted in the left FBD in Figure 5. The weight of the hand is neglected to simplify the formulas as it does not change the overall force analysis. This results in the following static formulas:

$$\sum F_x = F_{muscle} - F_{wrist,x} = 0 \tag{1}$$

$$\sum F_y = F_{wrist,y} - F_{g,drill} = 0 \tag{2}$$

$$\sum M_{wrist} = F_{g_{drill}} * a - F_{muscle} * b = 0 \tag{3}$$

Fig. 6: *Left:* Using a drill above shoulder height, resulting in an approximate ulnar deviation angle of 30 degrees. *Middle:* Using a drill at chest height, resulting in an approximate radial deviation angle of 1.5 degrees. *Right:* Using a drill at hip height, resulting in an approximate radial deviation angle of 4.8 degrees.

When drilling in a vertical wall, the same forces are present as when just lifting the drill. The added contact with the wall results in a vertical friction force and a horizontal normal force, as shown in the right FBD in Figure 5. This results in the following static formulas:

$$\sum F_x = F_{wall} - F_{wrist,x} = 0 \tag{4}$$

$$\sum F_y = F_{wrist,y} - F_{g,drill} + F_{friction} = 0 \tag{5}$$

$$\sum M = F_{g_{drill}} * a - F_{wall} * d - F_{friction} * c - F_{muscle} * b = 0 \tag{6}$$

With both the friction and wall forces creating a clockwise moment in the wrist, and only the gravitational drill force creating a counterclockwise motion, the muscle force can be described as follows:

$$F_{muscle} * b = F_{g_{drill}} * a - F_{wall} * b - F_{friction} * c \tag{7}$$

In most cases where the drill will be pushed against the wall, the moment from the wall force and friction force will be greater than that of the gravitational drill force. Therefore, in the situation of drilling in a vertical wall, the body has to create a counterclockwise moment in the wrist, ulnar deviation.

In conclusion, to help with both drilling and holding the drill, an orthosis must be able to support both clockwise and counterclockwise movements. Therefore, in terms of wrist movement, the device should support both radio and ulnar deviation.

2.4. Requirements

The previous problem definition results in a list of requirements for the orthosis. To clarify which requirements are a basic necessity for it to be functional and which can be scored on functionality, they are divided into product requirements and user requirements, respectively.

2.4.1. Product Requirements

- Orthosis needs to be portable through the work environment.
- Work movement and ROM should not change when using the orthosis.
    - Orthosis must function between 30° ulnar deviation and 5° radial deviation.
- Support the weight of the drill and the drilling motion.

2.4.2. User Requirements

- The orthosis must cause a lower muscle force, noticeable to the user, when the drill is lifted (radial deviation).
- The orthosis must cause a lower muscle force, noticeable to the user, when drilling in a vertical wall (ulnar deviation).
- Pronation and supination must be minimally restricted.
- The joint axis of the wrist must be minimally restricted.
- The orthosis should be lightweight.
- The orthosis should be simple to produce.

3. DESIGN OF A WRIST ORTHOSIS TO SUPPORT WORKING WITH A DRILL

All prototypes are designed according to the stated requirements and will be scored using the User Requirements, Section 2.4.2. The scoring is done to compare the concepts using a Harris profile. The concepts can be grouped into active, needing external power, and passive concepts, no external power needed. It is important for the prototypes to not force movement. Therefore, springs are used between the active components and the body.

3.1. Passive concepts

Passive concepts have the advantage that no external power or control mechanism is needed. There is no need for batteries to be attached to the body, and no computer is required. So, no cables or extra weight that limit the users freedom of movement. However, the drawback is that the control of the orthosis has to be mechanical or always active.

The first concept, Axis Fixation, fixates the movement of the radio/ulnar deviation axis without limiting flexion/extension and pro-/supination as can be seen in Figure 7. An attachment on the wrist is connected to the hand with a structure that is rigid in one direction and flexible in the other to only limit radio/ulnar deviation. Vertical sticks are attached next to each other, similar to sushi rolling mats, to fixate the radio/ulnar deviation while flexion and extension are still possible. This concept transfers the forces on the hand to the forearm bypassing the wrist. As mentioned in Section 2, drilling is done with the wrist in different angles. Therefore, the orthosis can be set in different angles using spring buttons, which are also commonly found on crutches. This system can only have a few predetermined selectable angles. If this is not precise enough, a hydraulic disk brake system can be used based on [28]. The disk brakes allow for high resistance, resulting in fixation, and can be set at any angle. The activation of the brakes can be active or passive.

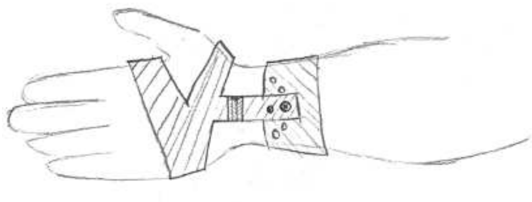

Fig. 7: Axis Fixation: Passive fixation of the wrist with adjustable angle using a spring button system.

The second passive concept, Passive Leaf Spring, uses flexible leaf spring structures between the hand and the forearm to increase the stiffness of the wrist. This allows movement in all directions but is pushed back when the hand moves in radio or ulnar deviation, similar to ligaments. The springs should be placed in line with the radio/ulnar deviation axis to limit unwanted forces on the wrist on the flexion/extension axis. However, this impact will always be present, as the springs will twist and bend during flexion and extension.

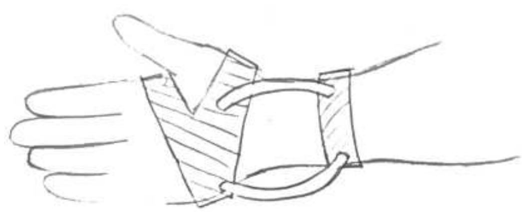

Fig. 8: Passive Leaf Spring: The wrist orthosis increases the stiffness of the wrist using leaf springs.

The last passive concept, the Support Arm, helps hold the drill in position using a support arm with a spring. One rod is fixated to the drill and the other to an attachment on the forearm. They are connected together with a hinge joint with an extension spring to transfer forces from the drill directly to the forearm, as shown in Figure 9. The extension spring is tensioned to push back when the drill is pressed against the wall. When the drill is being lifted, the spring pulls back to transfer part of the drill weight directly to the forearm. This concept does not impact flexion/extension or pro-/supination much because it is directly attached to the drill.

3.2. Active Concepts

As opposed to passive solutions, active solutions need power and a control mechanism. Although this is additional complexity and weight placed on the body, it can often be placed on the torso to limit the weight of the orthosis placed on the arm. The advantage of using active systems like actuators or motors is that they can be activated only when necessary. In addition, the force can be dynamic to suit different situations.

The Bowden Cables concept has a mechanism that can pull the arm in radial or ulnar deviation, similar to the Exosuit presented in

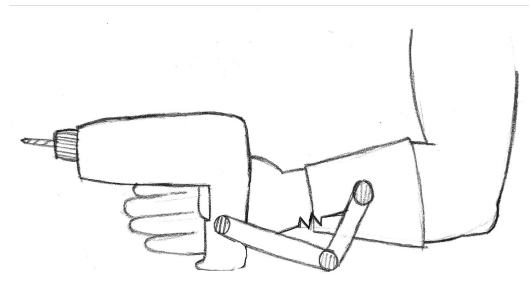

Fig. 9: Support Arm: forces ar transferred from the drill to the forearm using a spring system. The spring and beams push and pull the drill to a neutral position.

[6]. The concept uses Bowden cables in favor of actuators, as Bowden cables can bend, are lightweight and simple, in contrast to actuators [5, 13]. They are attached to a glove on the hand and a brace on the lower arm where the cables are actuated. The system is actuated by a motor that can turn in two directions to assist both radial and ulnar deviation. Flexible cables act as springs in the system to not force hand movement when it is not desired or when the maximum RoM is reached. A control mechanism and power supply are also needed for the motor to be activated when necessary in the correct direction and to be powered.

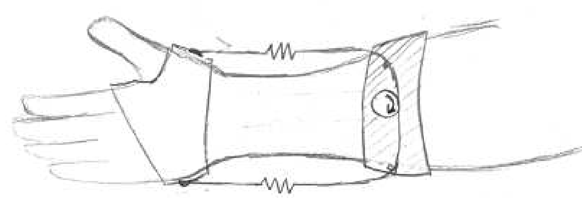

Fig. 10: Bowden Cables: Cables attached to the hand and forearm help move the wrist in radial and ulnar deviation.

The Active Leaf Spring concept is similar to the Passive Leaf Spring concept, which increases the stiffness around the wrist. The drawback of this passive concept is that it only works when the wrist moves away from the neutral position. To increase the force that the orthosis can exert and to apply force in a neutral hand position, the device must be active. The connection of the springs to the forearm attachment can be moved in line with the forearm, see Figure 11. This can be done with a motor or actuator when drilling or lifting the drill. This creates a tension in the spring that pulls the hand in radial or ulnar deviation.

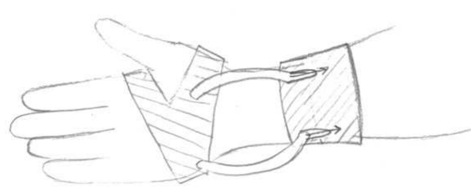

Fig. 11: Active Leaf Spring: The wrist orthosis increases the stiffness of the wrist by adding tension in the leaf springs by moving the attachment point on the forearm dorsal.

3.3. Prototype Testing

To get a general idea of how the concepts will perform, crude prototypes are constructed. The hand attachment is made from Velcro around the thumb to the ulnar side of the hand. A medical wrist brace is used as the forearm attachment and to fixate the wrist.

To test passive fixation of the hand, the brace is placed on the forearm and connected to the hand using Velcro, see Figure 12. The Velcro connecting the hand and forearm is placed on the sides of the wrist to fixate the deviation axis without fixating the flexion/extension axis. The flexion/extension axis is still a bit impaired, but to get a first impression, it is acceptable.

Fig. 12: Prototype of the Axis Fixation concept. A brace is placed on the forearm and connected to the hand with Velcro to limit movement in the deviation axis in the wrist.

The passive concept using a leaf spring is prototyped by connecting the hand to the forearm using Velcro, see Figure 13. The Velcro strips are attached so that obstruction to the flexion/extension movement is minimized. Although this is not as flexible as a leaf spring, the prototype pulls the hand to the neutral position while still leaving some room for deviation.

Fig. 13: Prototype of the leaf spring concept using Velcro. The hand and forearm are connected over the radial/ulnar deviation axis to pull back when a drill is lifted or being used. This prototype was used for the passive, as well as the active concept.

It is hard to make a crude prototype for the support arm concept. However, the effect of the concept on the body and the drill could be mimicked by applying an upward force to the bottom of the drill and a downward force to the side of the forearm attachment.

For the active version of the leaf spring concept, the same Velcro structure is used. To mimic the active part, the Velcro on the radial side of the hand is pulled when lifting the drill, and the Velcro on the ulnar side of the hand is pulled when the drill is pushed against a vertical wall.

The active concept using Bowden cables is first prototyped with a wooden hand and string to investigate the reaction of a hand without muscles (Figure 14). To further test the concept, the brace and Velcro are used to attach a rubber band between the hand and the forearm, shown in Figure 15. The rubber band is tensioned to act as if the Bowden cable is pulling the hand in radial deviation.

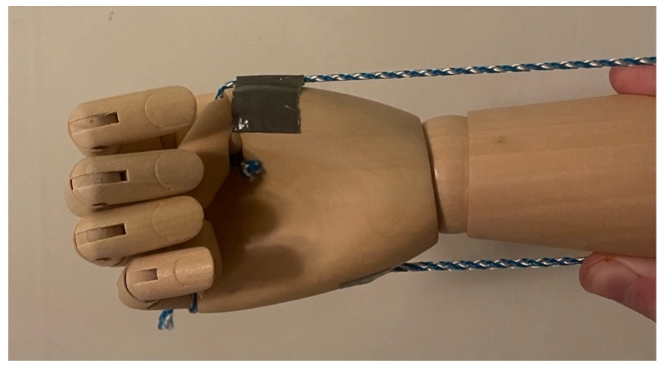

Fig. 14: Simple Bowden cable concept on a wooden hand using string to pull the hand in radial or ulnar deviation.

Fig. 15: Prototype of the Bowden cable concept using a rubber band as spring to pull the hand in radial deviation.

3.3.1. Prototype Performance and Fixes

An issue with most prototypes is the attachment method on the forearm. When there is a pulling force between the hand and the forearm, the attachment on the forearm slides toward the hand. This results in bad force transfer and therefore reduced functionality. To fix this, the attachment could be tighter, but this will be uncomfortable when the orthosis is used for longer periods. A solution for this constant pressure of an attachment is researched in [11], see Figure 16. An active anchor is presented that is activated only when necessary to reduce the otherwise constant uncomfortable pressure. However, for passive concepts, this would introduce the need for active systems to control and power the anchor. For active concepts, some control and power are already in place, but the anchor would add more complexity. Another solution is to anchor the brace to the upper arm. This should be done with a material that can bend and is flexible to stretching. A long tension spring would meet these requirements, as it can bend, and when the orthosis slides towards the hand the spring will pull it back in the proximal direction.

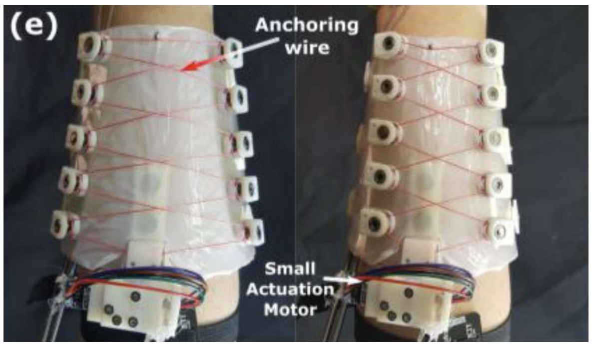

Fig. 16: Active anchor as stated in [11]. Wires on the brace can be tightened by a small actuation motor, resulting in better fixation of the orthosis on the forearm.

To get a visual representation of the strengths and weaknesses of the concepts, a Harris profile is used to score them with the user requirements, stated in Section 2.4.2. This representation of the concepts is used to help make a choice of which concept should be further developed. Table 1 shows the Harris Profile with the requirements, from top to bottom, in order of most important to least important. Each concept is given a score of: - -, -, + or + +, for each requirement. This is visualized with red and green boxes in the table.

As visible in Table 1, the first two passive concepts have negative scores for the most important user requirements, decreasing muscle load. This is the case because they only start to transfer force from the hand to the forearm when the wrist moves away from the position it is initially fixated in. During general drilling tasks, the muscles contract to keep the wrist in the desired position. This means that for both the concept that fixates the radial/ulnar deviation axis and the passive leaf spring concept, the muscle load will barely decrease using these concepts. In order to achieve a decreased muscle load, the leaf spring could be placed on one side of the wrist and be pre-tensioned to apply a force on the hand in the neutral position. However, this would limit movement in the other direction.

During testing of the prototypes using a drill, it is clear that ulnar deviation plays a small role when drilling in a wall. The wall-contact forces are transferred through the middle of the wrist, resulting in a most noticeable strain in the bicep and shoulder. Therefore, the lifting of the drill has the most impact on the muscle load in the wrist when working with a drill. To choose a concept to develop further, the requirement of decreasing muscle load for ulnar deviation is ignored.

Without the requirement of decreasing muscle load for ulnar deviation, the Support Arm and Bowden Cables concepts both score well in the Harris Profile, Table 1. The Support Arm is passive and, therefore, is simple to use and produce. However, it needs a robust attachment to the arm to prevent slipping and twisting on the forearm, which can limit pro- and supination RoM. The Bowden Cables concept has a slightly better score than the Support Arm. It can only be activated when needed, leaving the RoM in the wrist unchanged when not in use. But, as can be seen in Figure 15, it is hard to pull only on the radial/ulnar deviation axis without also moving the wrist to flexion or extension. Extra Bowden cables are necessary to counteract this unwanted movement in the flexion/extension axis. Because the Bowden Cables concept is active, the concept is much more complex and needs either EMG or other sensors to control it.

In conclusion, the Support Arm is a functional solution to support the task of lifting a drill without an overcomplicated design. The Bowden Cable concept may be used for a broader range of tasks but brings too much complexity. Therefore, the Support Arm will be further developed and tested.

3.4. Final Concept

The concept discussed in Section 3 is designed to assist with both radial and ulnar deviation. Since the ulnar deviation is less important during drilling tasks, the concept is reworked to focus on supporting the weight of the drill. The spring mechanism for the new design is based on that of the Freebal [29]. This mechanism can deliver a constant force, independent of the spring-beam angle. An L-shaped beam is used to bypass the handle of the drill and transfer the force to the bottom of the drill. For the system to be able to move, it is important to have a sliding contact between the drill and the support arm. For a drill with a flat bottom surface, as used in this paper, a flat support plate is able to slide. For the prototype version of the final concept, Figure 17, the L-shaped rod is split into two rods that can be fixed at different positions. This is done to make testing easier as the length of the rods is dependent on the drill as the rods have to bypass the drill handle.

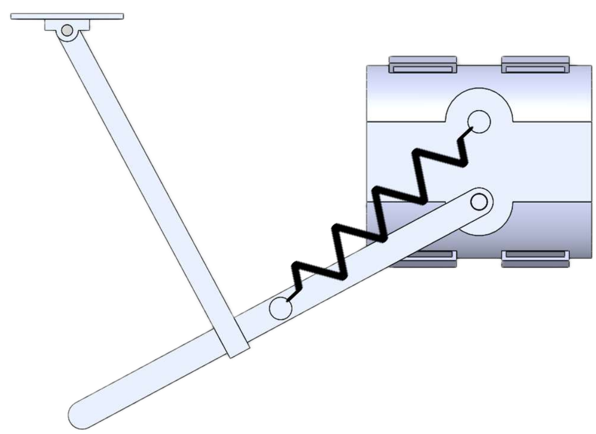

Fig. 17: Reworked Support Arm with an arm attachment and two beams in an L-shape to support a drill, visualized in SolidWorks.

The Support Arm consists of five parts, the arm attachment, the spring, an L-shaped rod to transfer the force from the spring to the drill (in this version split in two rods), and a plate to create an area to push the drill with. The parts are designed in SolidWorks [30].

To evaluate the viability of the concept, a wrist and drill model for radial/ulnar deviation is added to the assembly in SolidWorks; see Figure 18. Moving the drill to different positions results in a slight change in the contact point of the orthosis with the drill. This is necessary as fixation of this point would fully lock movement in the whole model. In addition to this contact point, all other joints and connections remain fixed; the orthosis is 3D printed for testing with an UltiMaker S5.

Table 1: Harris Profile to visualize the performance of the concepts for the user requirements

	Axis Fixatation				Passive Leaf Spring				Support Arm				Bowden Cables				Active Leaf Spring			
	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +	- -	-	+	+ +
Decrease Muscle Load - Radial Deviation																				
Decrease Muscle Load - Ulnar Deviation																				
No restricted wrist joint axis																				
Pronation / Supination Not Impaired																				
Lightweight Orthosis																				
Low Production Complexity																				

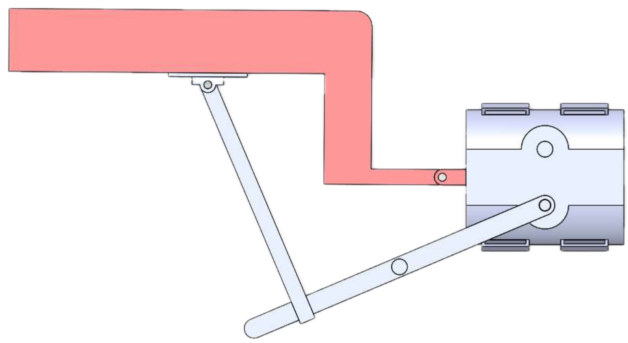

Fig. 18: Design expectation of the Support Arm, in silver, with a model of the drill and wrist, in red, in SolidWorks.

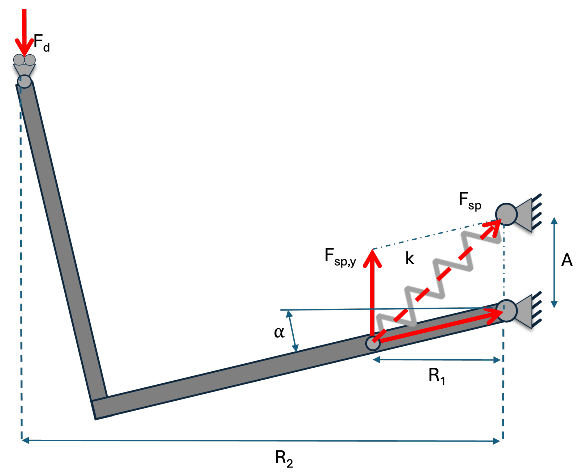

Fig. 19: Overview of the support of the orthosis, based on the Freebal [29]. The spring force is split in two components, towards the attachment point of the beam and the vertical force Fsp, y.

4. FORCE ANALYSIS AND DESIGN IMPROVEMENTS

4.1. Force Analysis of the Orthosis

To validate that the orthosis has an impact on the necessary muscle load, a force analysis is performed. The force analysis in Figure 19 is based on the Freebal but modified to generate an upward force. As stated in [29], the force on the drill, F_d, is independent of the angle of the spring and the angle of the beam when using an ideal spring. This is desirable as the drill will always have the same supporting force, regardless of the position of the drill. A Free Body Diagram of the beams in the orthosis is presented in 20.

The force on the drill, F_d, is always the same because the spring force, F_{sp}, can be split into its x and y components to create a parallelogram where $F_{sp,y} = A * k$. Since A and k always have the same value, $F_{sp,y}$ is a constant force.

To determine the forces in the orthosis, Figure 19, the spring mechanism and the drill split to formulate an equation for the force on the drill, F_d. The masses of the parts of the orthosis are ignored as they are very light weight compared to the weight of the drill.

The Vertical Spring Force ($F_{sp,y}$):

$$F_{sp,y}[N] = A[mm] * k[N/mm] \tag{8}$$

The vertical compensation force at the end of the rod with the sliding component, (F_d), can be determined using the sum of moments in the attachment point of the rod:

$$\sum M[N/m] = F_{sp,y}[N] * R_1[m] - F_d[N] * R_2[m] = 0 \tag{9}$$

$$F_d = F_{sp,y} * \frac{R_1}{R_2} \tag{10}$$

Combining this with Equation 8 gives:

$$F_d = A * k * \frac{R_1}{R_2} \tag{11}$$

The force on the drill in Figure 20 can be derived from the sum of moments in the wrist: influenced by the weight of the drill $F_{g,drill}$ and the supporting force F_d.

$$\sum M[Nm] = F_d[N] * c[m] - F_{g,drill}[N] * a[m] = 0 \tag{12}$$

$$F_d = F_{g,drill} * \frac{a}{c} \tag{13}$$

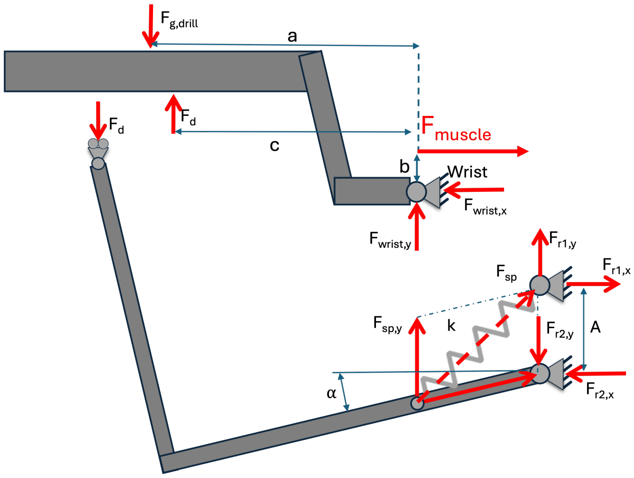

Fig. 20: Forces on the orthosis and drill. Spring mechanism generates a force at the slider. This slider transfers the force to the bottom of the drill, counteracting the moment in the wrist generated by the gravitational force.

To fully support the weight of a drill when the supporting force is perfectly below the center of gravity of the drill ($a = c$), F_d must be equal to the gravitational force of the drill: $F_{g,drill} = Weight[kg] * g[m/s^2]$. Working back to the spring using the previous formulas, this gives the following formulas:

$$F_{g,drill} = F_d \tag{14}$$

$$Weight * g = A * k * \frac{R_1}{R_2} \tag{15}$$

The values of the variables for the final design are shown in Table 2. The drill used for this research is a BOSCH UBH 2/20SE [31].

Table 2: Values used in the force equations.

Variable	Value	Unit
Drill Weight	2.3	$[kg]$
g	9.81	$[m/s^2]$
k		$[N/mm]$
A	35	$[mm]$
R_1	100	$[mm]$
R_2	175	$[mm]$

Only variable k is not defined because the spring can be switched in order to choose how much force the orthosis supports. R_1 and R_2 can also be changed in the design of the orthosis but for this research and prototype, the values are fixed. Entering these values in equation 15 results in the following value for k to fully support the weight of the drill:

$$2.3 * 9.81 = 35 * k * \frac{100}{175} \tag{16}$$

$$22.563 = 20 * k \tag{17}$$

$$k = \frac{22.563}{20} \approx 1.128[N/mm] \tag{18}$$

The sum of moments in the wrist can be calculated again from the FBD of the drill in Figure 20. $F_{g,drill}$ and F_d have a different moment arm to the wrist as the orthosis will not always support the drill at the center of mass. This results in the following formula:

$$\sum M_{wrist} = F_{g,drill} * a - F_d * c - F_{muscle} * b = 0 \tag{19}$$

Assuming $k \approx 1.579$, the orthosis will push with as much force as the gravitational force of the drill: $F_{g,drill} = F_d$. Replacing F_d in the formula results in the following equations.

$$\sum M_{wrist} = F_{g,drill} * a - F_{g,drill} * c - F_{muscle} * b = 0 \tag{20}$$

$$\sum M_{wrist} = F_{g,drill} * (a - c) - F_{muscle} * b = 0 \tag{21}$$

Formulated like this, the sum of moments in Equations 21 and 3 are similar. $F_{g,drill}$ is constant and the same value in both scenarios. The moment the muscles have to contribute, $F_{muscle} * b$ is not the same but can be calculated for each scenario:

$$WithoutOrthosis : F_{muscle} * b = F_{g,drill} * a \tag{22}$$

$$WithOrthosis : F_{muscle} * b = F_{g,drill} * (a - c) \tag{23}$$

From these equations it can be concluded that the moment created by the muscles and, therefore, the muscle force is less when using the orthosis than without the orthosis as long as $c > 0$. If c is equal to a, the drill is supported at its center of gravity, so there is no gravitational force of the drill on the hand, as already discussed in the calculations for the spring constant.

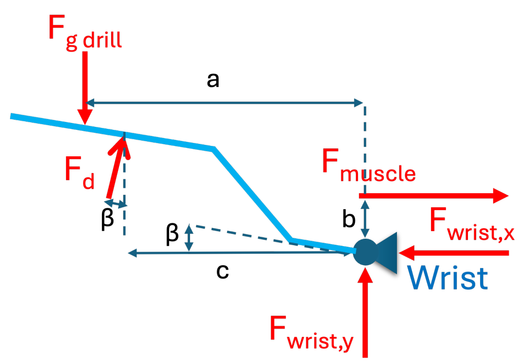

Fig. 21: FBD of the wrist and drill with the supporting force and angle of the wrist. This angle, β, of the wrist is the same as the angle of the force F_{d_β} perpendicular to the bottom of the drill.

To find the impact of the angle of the wrist on the Support Arm force and the moment in the wrist, the FBD must be expanded to include the angle of the wrist. The drill and the hand are considered to be one rigid structure as seen in Figure 21. The angle of the wrist results in a decrease in vertical force transfer to the drill, as the force from the orthosis is always in line with the attachment points of the orthosis. If the drill is at an angle and the force is vertical, only the perpendicular component of the vertical force can be transferred to support the wight of the drill. The parallel component of the vertical force results in shifting of the contact point as there is a slider between the drill and the support arm. For the following calculations, the force is assumed to be vertical. Including the angle of the wrist to the equation for the moment in the wrist results in:

$$\sum M_{wrist} = cos(\beta) * F_{d\_\beta} * c - F_{g,drill} * a - F_{muscle} * b = 0 \tag{24}$$

The result from the angled wrist is that the vertical force from the orthosis on the drill is lower. In the scenario where the wrist is in a position of 5 degrees of radial deviation, the efficiency is still 99,6%. For 30 degrees ulnar deviation, the efficiency is 86,6%. The angle of the forearm has a similar effect on the force transfer to the drill. This angle results in an angled forearm attachment and therefore in an angled force from the orthosis. This is not desirable if the drill is horizontal. However, if the drill is at an angle and this is matched by the forearm attachment, the force transfer is still optimal as it is perpendicular to the bottom of the drill.

4.2. Improvements of the design

Figure 22 shows the first prototype with elastic band used as the spring. This is not the ideal spring the calculations are based on as the ideal spring is necessary for the force to be constant. However, for testing, it still gives the user an idea of whether the prototype is functional as there is a noticeable difference in load when the orthosis is used.

The prototype is designed to work with the arm attachment in line with the drill. This results in the force being in line with the gravitational force of the drill. The expected use is shown in Figure 18, where the forearm is expected to be in line with the drill. In reality, this is not the case, as can be seen in Figure 22.

Fig. 22: First 3D printed prototype of the Support Arm. Tested with an elastic band as the spring.

Figure 22 shows the forearm at an angle from the drill. This results in an angled force from the spring mechanism and a decreased force from the orthosis lifting the drill. To fix this issue, the attachment points of the drill have to be angled to align with the gravitational force when the drill is used. To evaluate the angle necessary for this to happen, pictures are taken of a person using the drill, both with and without orthosis. These are analyzed with Kinovea [27] to determine the angle. The pictures can be found in Appendix A, this resulted in an angle for the attachment points of 20 degrees to align the force to be vertical on the drill.

The arm attachment of the first design is also too large. This results in shifting and twisting around the arm when the support is in contact with the drill. To remedy this, the diameter of the attachment is reduced to better fit the forearm. The width of the forearm needs to be large enough to counteract twisting of the attachment on the forearm but small enough to not limit pro- and supination.

4.3. Final Design

The final design has the previous improvements applied: The spring mechanism attachment points on the forearm attachment are angled, and the forearm attachment is made smaller to better fit the wrist. This is first modeled and evaluated in SolidWorks, Figure 23. Afterwards, the changed parts are printed and assembled for the final prototype, Figure 24.

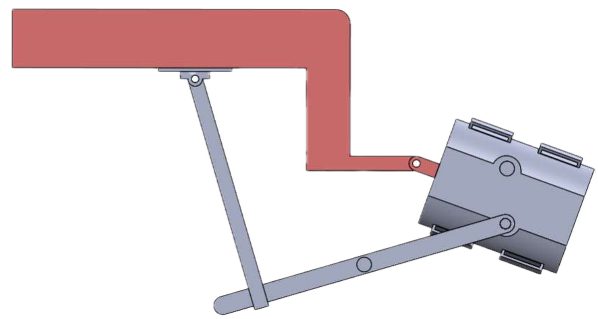

Fig. 23: Improved concept (in gray) with the connection points on the forearm attachment at an angle of 20 degrees.

Testing the final prototype resulted in a noticeable decrease in the perceived weight of the drill. Although the rubber bands do not support the drill in the same way an ideal spring would, holding the Support Arm against a kitchen scale resulted in a weight of approximately 450 gram $\approx$ 4.4 Newton.

Fig. 24: The prototype of the final concept with angled attachment points for better force transfer and a better fitting forearm attachment.

The inaccuracy of the force transfer is also a result from the simplification of the calculations. Because the calculations are only done in a 2D plane and the wrist is a three-dimensional joint, the forces might not only work in the 2D plane. The force to support the drill will not be perfectly below the center of gravity in the z-axis. In Figure 25, the front of the drill is shown with the orthosis, showing where the force from the orthosis is applied. This can result in twisting of the drill in the hand as a moment is generated by the force being more towards the left or right of the drill. This will increase the necessary gripping force and the pro-/supination force of the user to keep the drill in position.

Fig. 25: The final prototype, pictured from the front, with the force of the orthosis on the right side of the center of gravity of the drill.

In a 3D assessment of the orthosis, the forearm attachment will also twist and shift. The beams of the orthosis are in a fixed position with the drill. The spring and beam are connected to the forearm attachment and create a moment that is only counteracted by the contact with the forearm. This contact is not perfect as the skin moves and the strips that hold the orthosis need to be tight for the best results. This results in a transfer of force to the elastic skin of the forearm, leading to a decrease in the force on the drill.

5. DISCUSSION

The Support Arm orthosis is designed to decrease muscle load when lifting a drill using an ideal spring mechanism. This mechanism ensures a constant vertical force on the drill, independent of the angle of the beam and the spring. Therefore, the muscle force decreases as well as the bone contact forces that come with high muscle forces. Changing the spring can increase or decrease the supporting force of the orthosis, depending on the weight it needs to support. The design in this paper is focused only on supporting a drill during radial deviation. However, with some changes to the support structure, other radial deviation lifting tasks could also be supported.

Looking back at the requirements stated in Section 2, the orthosis meets all these requirements except for the support during ulnar deviation, as this requirement is excluded after testing the concepts. The experienced muscle load of the user is lower when using the orthosis without restricting movement in the wrist or forearm. The orthosis is also portable as it is a passive orthosis attached only to the forearm. It is also lightweight and easy to produce.

Using the orthosis is fairly easy; when the orthosis is attached to the forearm and makes contact with the drill, it can be used without having to think about it. Attaching the attachment to the forearm can be challenging, but it can be done independently by the user. When the drill is not in the hand, the orthosis moves up, hindering the user. This and other limitations will be discussed further in the next subsections.

5.1. Limitations

Although several improvements are made to the design, there are still limitations. For the purpose of prototyping, the support beam structure consists of two parts. This has no final functional purpose, except to change the distance of R2 during the initial tests; see Figure 19 for reference.

Because ease of use is important for user acceptance of the orthosis, the design is simple to use and minimally obstructive. However, no further improvements are made to increase the comfort of the forearm attachment. The attachment of the orthosis to the forearm and the drill could be improved to make it easier to use and less obstructive when the drill is not held.

The force analysis to calculate the necessary spring constant, performed in Section 4, is based on the test setup with a BOSCH UBH 2/20SE drill. The values for R1 and R2 are based on the prototype, but could be further optimized. R2 has to be large enough to evade the drill handle and the hand, in this case 175 mm. For R1 a value of 100 mm is chosen to keep the mechanism compact. However, increasing this value would decrease the necessary spring constant. Based on the drill and use case, these values should be optimized to support the drill as necessary. In these calculations, the weight of the orthosis is not considered. The 3D print indicated that the parts of the orthosis would be approximately 65 gram, excluding the spring; in relation to the drill of 2.3 kilograms. For a better understanding of the forces in the orthosis, this should be considered, as well as the stiffness of the beams and other parts that might bend.

A big oversight in the design of the support arm is that when the extra part, the vertical part of the L-shaped beam, is added to the beam mechanism with the spring, the moment arm changes when the angle α changes. Therefore, the system does not work as the Freebal on which it is based. Because the moment arm becomes larger as alpha increases, the force on the drill decreases as it is lowered and increases as the drill is moved upward. This could also have a beneficial effect, as drilling at an upward angle results in a higher support force on the drill. However, it is not an intended part of the design. The calculations in Section 4 are based on values where $\alpha = 0$, which would mean the drill is angled upward. In the neutral position where the drill is horizontal, as seen in Figure 24, $\alpha \approx 10[degrees]$. This results in an increased moment arm, R2, of 3 cm and therefore a decrease in force on the drill by 14,5%. Lowering the drill further with ulnar deviation in the wrist would further decrease the supporting force, and a higher spring constant would be necessary to counteract the full weight of the drill for the lower angles.

In addition, in the force analysis, the assumption is made that the drill and the hand are one rigid system. In reality, this is not the case. The gripping force in the hand to hold the drill is controlled by muscles that also work over the wrist. Therefore, if the gripping force must be increased to hold the drill with the orthosis attached, the muscle force in the wrist automatically increases as well, and this is not desired. As mentioned in Section 4.3, the force analysis only evaluates the orthosis in a 2D plane. The supporting force from the orthosis can twist the drill if it is not applied on the center of gravity. This would require the hand to grip tighter, and pro- or supination would be necessary to keep the forearm from twisting. This effect of the orthosis is not evaluated in this paper and is an important step in further improving the Support Arm.

To improve the vertical force on the drill, the attachment points on the orthosis are angled at 20 degrees. This is based on limited testing on a single test subject when drilling at chest height. This angle of 20 degrees might not be the optimal angle. More testing is needed to further improve this part of the orthosis. As mentioned in Section 2, the full range of motion when using a drill extends to 30 degrees ulnar deviation and 5 degrees radial deviation. As the orthosis moves in a position where the attachment points are not in line with the gravitational force on the drill, the supporting force works at an angle and is less effective.

The attachments to the drill and forearm are functional, but do have some limitations. The current drill attachment is a flat support plate but does not have a fixed connection to the drill. This can result in shifting, moving the location where the force of the spring mechanism is exerted. In the force calculations, the assumption is that the forearm attachment is fixed and therefore the full spring force is transferred to the drill. However, when the weight of the drill is transferred to the forearm, the attachment on the forearm can twist if it is not tightly fixed. This means that part of the spring force is not exerted on the drill but on the forearm, resulting in less support to lift the drill.

The orthosis is designed to be attached when a drill is used. However, sometimes the user will put the drill away for a short period of time, keeping the orthosis on. With the current design, the beam will move up until the spring can not contract further. This is not ideal, as the beams will shoot up above the forearm, making it difficult to maneuver the hand. Donning and doffing is also harder when the orthosis occupies a lot of space because the attachment strips will be harder to reach.

For the purpose of this paper, in the design phase, only drilling in a vertical wall is considered. This is not fully representable for all real-life use cases, as sometimes the wall is at an angle or drilling in the ceiling is necessary. In these cases, the force on the drill is not in line with the gravitational force on the drill, resulting in a decrease efficiency to 86,6%. This results in a lower possible force transfer of the orthosis.

While the force analysis indicates that the orthosis can support the weight of the drill and therefore reduce muscle load, the orthosis has not been tested with participants. Using a kitchen scale to evaluate the force generated by the spring mechanism results in a force of approximately 4.4 Newton. For this test a rubber band is used instead of the ideal spring that is used in the calculations. Although not fully representative of the concept presented, this shows that the orthosis is capable of generating a noticeable force to support a drill.

5.2. Future Research

To further evaluate the concept, testing the user experience of several participants, drilling at varying heights, is necessary. This should be done with an ideal spring with a known spring constant to be able to compare the results with the calculated expected results. During these tasks, the force between the orthosis and the drill should be measured using force plates. This can be compared with the force analysis to validate the efficiency of the design.

To validate whether the orthosis decreases the muscle load necessary to lift a drill, electromyography (EMG) measurements of the forearm should be performed. Although muscle activation from EMG measurements is difficult to compare with actual muscle force without a musculoskeletal model [32], increased muscle activity is related to increased force [33]. Measurements have to be made when the drill is held with the orthosis to support it and without the orthosis. EMG markers should be placed at the same location for the two measurements. Therefore, it is advised to do them consecutively, without removing the markers between measurements. The muscles to target could be: m. flexor carpi ulnaris, m. flexor carpi radialis, m. extensor carpi ulnaris, m. extensor carpi radialis longus [12, 25].

Some muscles in the forearm are biarticular and can move the elbow joint as well as the wrist. In order to focus on muscle activation to support the wrist, the forearm should rest on a fixed surface; a similar setup as used in [33]. This should decrease the muscle activity to stabilize the elbow. To make the choice of using EMG to estimate muscle force, the Consensus for Experimental Design in Electromyography matrix proposed in [32] could be used.

5.3. Recommendations

The further development of the Support Arm orthosis should focus on improving user acceptance and optimizing the spring mechanism. With the current design, whenever no drill is held, the support arm moves up until the spring is at its minimum length. This results in an inconvenient location of the support when a drill needs to be supported. To help keep the support arm around the location where the drill is supported, a stop on the forearm attachment should be considered. To further improve the user comfort of the orthosis, some cushioning should be added to the forearm attachment and sharp corners should be rounded. This makes it more comfortable for the wearer and helps to better fit the attachment around the arm.

Depending on the drill, or other supported object, R2 has to be changed for the support force to be below the center of gravity. The weight of the drill can also differ. Therefore, the force analysis must be adjusted to find fitting values for R1 and the spring constant to support the weight of the drill. The angle of the spring mechanism on the forearm attachment needs further investigation. The current angle is based on one test subject using the drill at chest height. As can be seen in Figures 31 and 32 in Appendix A, this improvement may not be enough for this use case, as the wrist is now at an angle of about 25 degrees to the drill.

As mentioned, the moment arm of the Support Arm concept is not independent of the angle α. This is the result from the extra part on the beam that is fixated at a right angle. In order for the Freebal spring mechanism to work as intended, the force of the spring and the supporting force must be applied at fixed distances on the same straight beam. This results in the angle α having no effect on the magnitude of the support force. To realize this, the beam between the drill and the support beam should be connected with a hinge joint. Then it should also be connected to the drill with a slider and a hinge to ensure the beam is always in line with the force generated by the spring mechanism, see Figure 26. A solution to keep the slider aligned above the end of R2 is necessary to ensure that the moment arm does not change.

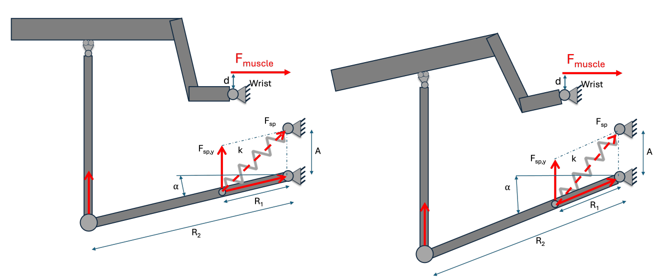

Fig. 26: A suggested correction of the Support Arm prototype. The L-shaped beam has a hinge so the vertical beam can be aligned in line with the vertical spring force.

To keep the force on the drill in the opposite direction of the gravitational force on the drill, the attachment points on the forearm must be in line with those forces. When the drill is used at an angle, the forearm itself cannot move to such a position. To align the attachment points, they could be placed on a rotating plate that can be oriented in line with the gravitational force. However, when the drill is at an angle, the contact point is also at an angle and the support plate will slide. This will reduce the supporting force on the drill. Some sort of locking mechanism between the support plate and the drill is needed to support drilling at an angle or even on the ceiling.

Other optimizations should be made to the attachment between the drill and the orthosis and to the forearm attachment. To ensure a good contact between the support and the drill, the current plate must be adjusted. There is some shifting necessary to not limit the degrees of freedom of the system. Therefore, if the drill is to be modified, it has to have a sliding connection to the Support Arm. The other option is to shape the support plate to better fit around the bottom of the drill without having to modify the drill itself.

An important factor of the design is the forearm attachment. For maximal force transfer, the attachment is perfectly fixed to the forearm. However, this is hard to accomplice as the skin and muscle move beneath the attachment. Tight attachment reduces the shifting but is uncomfortable. The active anchor from [11] resolves the issue of constant tight fixation by only tightening when necessary, but the fixation will still be uncomfortable. A solution could be to fit the attachment around bone points near the wrist. This can be challenging as the skin still moves and the bone points have a different shape for each person. Another option is to add an extra attachment more proximal on the forearm to help in preventing the twisting. This extra attachment has to be connected to the current attachment with a rigid structure. This larger attachment on the forearm has the drawback that pronation and supination will be more impaired. Further development of the current orthosis should look into options of fixation the attachment to the forearm.

Finally, the Bowden Cable concept discussed in Section 3 also scored high in the Harris Profile. The Support Arm is chosen because it is simple and effective in supporting the weight of a drill. However, the Bowden Cable concept is promising for more use cases. One drawback during prototype testing is that the concept also pulls in the flexion and extension directions. To fix this, more Bowden cables could be added, resulting in cables for flexion, extension, radial deviation, and ulnar deviation. Because this concept is active, a control system is needed to activate the Bowden cables. This can be done by the user via button presses. Activation could also be done from EMG measurements, when the muscles activate, the corresponding Bowden cables also tighten. Lastly, the control could also be connected to a glove with pressure sensors. If there is a force on the hand that pushes the wrist in ulnar deviation, the pressure sensor detects this and activates the Bowden cable to pull the wrist in radial deviation. This system is much more complex than the one presented in this paper and is beyond the scope of this research. However, further research could result in an orthosis capable of supporting all movements of the wrist.

6. CONCLUSION

The Support Arm orthosis is able to support a drill when it is being lifted, reducing the experienced muscle load during radial deviation. The supporting force of the orthosis can be easily modified depending on the task. More research is needed to obtain more information on the full effect of the orthosis on the wrist. The concept should be recreated with one L-shaped beam and an ideal spring. Improvements could be made to the drill support plate to improve the force transfer when drilling at an angle. The forearm attachment should also be improved to increase comfort and contact surface for better force transfer. EMG measurements, combined with a musculoskeletal model, could provide more insight in the muscle activity and muscle force with and without orthosis. For the design of a wrist orthosis, it is important to minimize impact on the RoM of the wrist and forearm, especially for use in construction and industry work. The Bowden Cable concept is promising but has a high complexity. However, it could be a viable solution for an orthosis that must support all movement in the wrist. For the goal of this research, to support employees in construction and industry work when working with a drill, the Support Arm is a functional solution that can decrease the necessary muscle force and, in doing so, also decrease the bone contact forces in the wrist.

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APPENDIX

A. RESEARCH FOR IMPROVEMENTS

The forearm is at an angle in perspective to the bottom of the drill, resulting in a lower force transfer. Image analysis is performed using Kinovea to define the angle. One arm of the angle is parallel to the bottom of the drill, the other is in line with the forearm. This is done without orthosis, Figures 27 and 28, and with orthosis, Figures 29 and 30:

Fig. 27: First measured angle between the forearm and the drill without an orthosis.

Fig. 28: Second measured angle between the forearm and the drill without an orthosis.

Fig. 29: First measured angle between the forearm and the drill with the orthosis.

Fig. 30: Second measured angle between the forearm and the drill with the orthosis.

After modification of the forearm orthosis to compensate for the forearm angle, new photos are taken and analyzed in Kinovea. Figures 31 and 32 show these photos with the angles.

Fig. 31: First measured angle between the forearm and the drill with the angled forearm attachment.

Fig. 32: Second measured angle between the forearm and the drill with the angled forearm attachment.