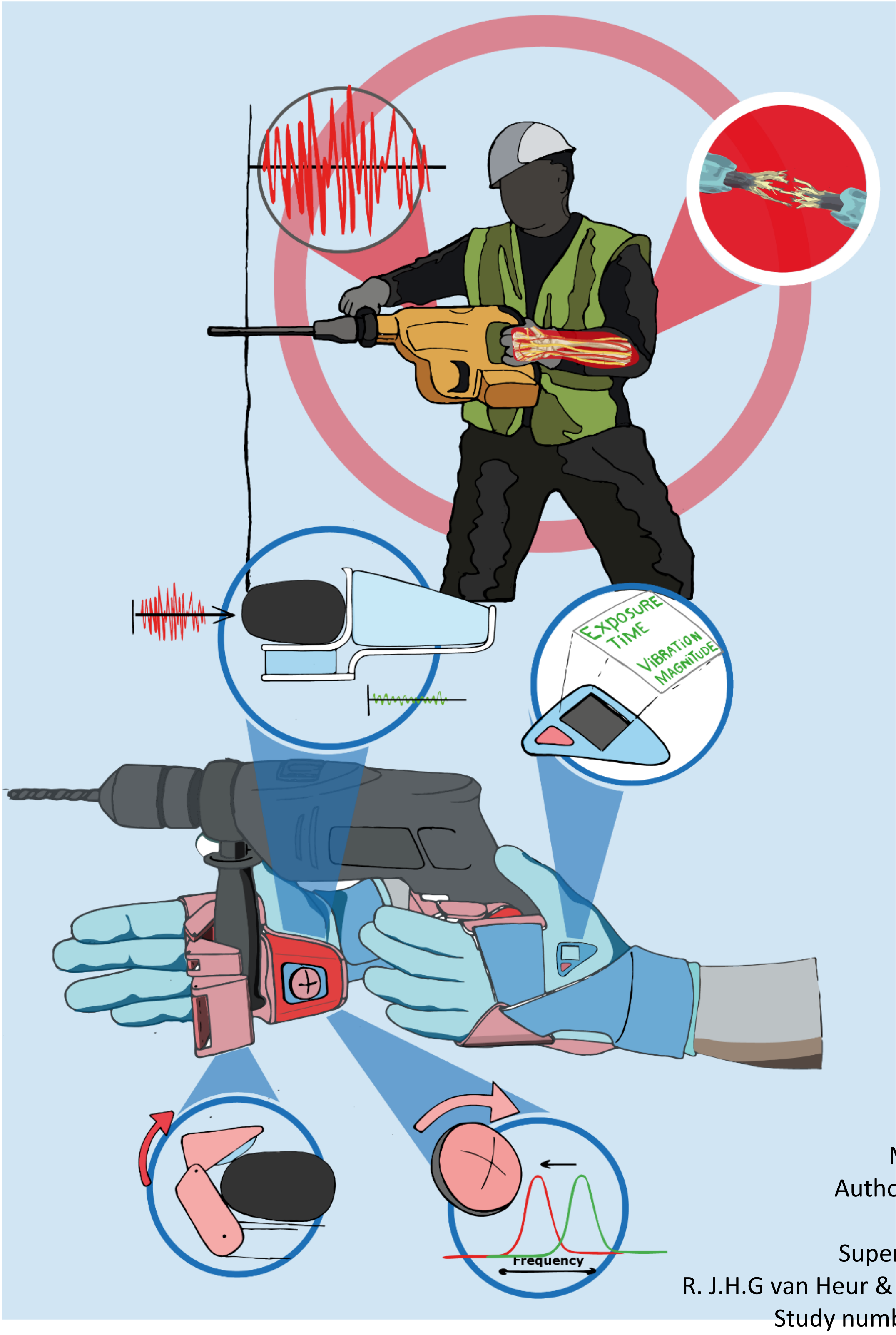
Design driven risk mitigation of work related hand-arm vibrations.



Master thesis
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Executive summary

Vibration exposure is a significant problem in the construction industry. However, the consequences remains underappreciated and largely unaddressed because vibration exposure is difficult to measure and the symptoms often appear after decades of exposure.

These symptoms, collectively called hand-arm vibrations syndrome, include loss of sensory and motor function in the hands. Prolonged exposure can lead to these symptoms becoming permanent and severely debilitating Avoiding construction workers are often reluctant to report discomfort and are in a weak position of negotiating better work conditions. The companies on the other hand find adhering to the vibration exposure limits difficult because there are no viable means of reducing exposure.

In this thesis a protection device is developed that is specifically aimed to alleviate these problems concerning hand-arm vibrations. Special consideration is taken to directly address vibration exposure. To this end, experiments are done to explore and validate a vibration mitigation technology. A prototype is then developed to implement the result towards a useable protection device.

1. Introduction

Since 1760 [1], with the coming of the industrial revolution, the productivity of the individual laborer increased greatly. With this revolution a close interaction between human and machinery suddenly became much more prevalent, along with a host of new occupational hazards. With the advent of the first power tool in 1895 [2], this machine driven productivity could now leave the workshop and be brought to anywhere the worker would carry it. An ever increasing share of societies productivity was now achieved through the use of these power tools. Today, especially in construction work and manufacturing, power tools are omnipresent and irreplaceable. This interaction between man and tool brings incredible efficacy to the workplace, yet it also exposes the human body to conditions to which it is ill suited to endure such as excessive heat, toxins and mechanical vibrations.

Work related vibrations are an under-appreciated problem that often goes overlooked by both employers and employees. Most work related vibrations relate to full body vibrations found mainly in vehicle driving professions. This usually involves well understood problems in widely prevalent professions such as bus- and forklift drivers. Hand-arm vibrations on the other hand is a widely spread phenomenon found across a myriad of rather obscure professions (e.g. mortar chiselers), and otherwise in smaller work activities within the more prevalent professions (e.g. concrete drilling in construction work).

Whenever a worker performs any type of percussive action using a handheld tool or operates any powered hand held tool, Hand-arm vibrations becomes a factor. On top of that, difficulties in assessing the risk of Hand-arm vibrations has resulted in a lack of research and practical solutions, and even in less regulation enforcement by inspection services. The activities are typically not done for the duration of a work day, but rather as part of a broader work pattern. As a result the inspection service has difficulty assessing how long a worker has been exposed. This results in a relatively large health problem among workers, which is not commonly known and thus not adequately addressed by governments, employers and employees.

Long term exposure to Hand-arm vibrations significantly decreases overall quality of life, impairing the worker in work as well as in their daily life activities. In a 2001 study among Hand-arm vibrations exposed males, 42 percent of participants reported to have difficulties in performing daily tasks such as handwriting, opening lids, picking up objects and working in a cold environment, due to pain and reduced grip force [3]. What should also not be overlooked is that because exposure to Hand-arm vibrations impairs the use of people’s hands, it impairs their very ability to do that same job. This means that for people with debilitating consequences from Hand-arm vibrations, it is very difficult to find alternative employment. Any work they are likely to find, would also involve working with their hands.

Currently the Dutch labor inspection (SZW Inspectorate) has guidelines and regulations stating the maximum exposure to vibrations, however these regulations are often not enforced strictly, since the maximum exposure times of most power tools are easily exceeded.
Even when adhering to the maximum exposure to vibration that is currently enforced, over a span of 12 years 10% of workers still experience long-lasting health problems (i.e. Hand-arm vibrations) leading to lifelong disability [4].

With this thesis work I aim to develop a personal protection device that will protect these workers sufficiently against hand-arm vibrations, and prevent injuries such as hand-arm vibration syndrome. Power tool manufactures already try to optimize vibration damping by including damping techniques in the tool itself, however these remain insufficient.
In addition, this thesis will serve as the ground work for a startup. This entrepreneurial approach will provide a position of greater initiative in targeting hand-arm vibrations, without the need to wait for another party to bring my findings into action.

2. Assignment deconstruction

2.1 Problem definition

This project is predicated on the phenomenon that workers in the construction industry are exposed to hand-arm vibrations. This exposure causes injury end eventual disability. To establish an appropriate framing in which to address this problem, the underlying cause of the problem must be understood first.

2.1.1 A need for power tools

The construction industry is defined by its use of concrete, brick and steel in building new buildings and infrastructure. Inherent to working with these materials is the need for high powered machinery and tools that can produce the necessary high impact forces and pressures (e.g. for drilling, breaking and sawing).

Modern construction companies are mechanised to a large extent, or have even eliminated entire in situ work activities as in the case of building with pre-fabricated building parts. But this modernisation cannot account for the entire building process, and many work activities still require the attention and coordination that only an individual worker using a handheld power tools can provide.

2.1.2 Economic pressure

The construction companies are under market pressure to perform competitively, which means that they are bound to use which ever method is cheapest. With regard to power tools this might cause the company to choose a heavier power tool for the job, or to make their employees to do the activity for extended periods of time.

The activities that require the use of these power tools are often hard to avoid. Either alternative methods without vibrations are not available, or are simply not economically viable (i.e. too expensive).

The workers, who depend on their job as a construction worker for their livelihood, are exposed to hand-arm vibrations emitted by the power tools that they use. As a result from these vibrations they risk developing long lasting injuries that jeopardize their quality of life and even their employment. In severe cases these injuries become permanent and heavily debilitating. This is why hand-arm vibrations poses an untenable situation for the construction industry, that urgently needs to be solved.

2.2 Assignment

The goal of this the design process laid out in this thesis is to remove the tension that exist between productivity (i.e. economic pressure), and personal wellbeing of the person doing the work activity. This can be achieved by offering the employer a way of creating a safe work situation, while not sacrificing productivity. Any proposed solution should therefore not impede the productivity of the actual work activity, and that directly addresses the problem of hand-arm vibrations in the workplace.
The core aim of this project will therefore be to design a product that significantly decreases hand-arm vibration exposure to the user while operating a power tool. Solutions to this

problem that just involves monitoring, or aim to limit the exposure by decreasing work time are not desirable.

2.2.1 Towards a startup

This project is also aimed to provide a basis for a startup. Although an eventually successful capitalization is a goal in itself, it can also help claim initiative in bringing about change with regard to hand-arm vibrations. The product should have the potential to be applicable to a wide variety of work activities, or otherwise address a work activity that is practiced by a large number of people. This is to ensure that the product will apply to a large market. Also, it will help to avoid developing a product that narrowly serves a relatively obscure work activity, and there for having very little impact.

The focus in terms of market will be on the European Union, as regulations in the EU are uniform. Europe is a large economic zone with a high standard of safety and regulation, relative to other large economic zones such as USA or China. This will further help the marketability of a protection device.

In conclusion, the goal from an entrepreneurial point of view will be to develop a protection device that is effective at solving a pressing safety matter(high user value), while addressing a large market(potential high demand).

2.3 Approach

The first step of achieving this is to investigate the nature of the problem by conducting a multidisciplinary analysis. This includes fields such as the biomechanics involved in handling a power tool, and the particular pathology of hand arm vibration syndrome.

With regard to designing a solution the following things will be taken into consideration:

- The expectation is that it will be difficult to design an effective protection device that outperforms existing measures. That is why the aim is to also counter the problem in an alternative way that will come from a deeper, multi-disciplinary understanding of the problem. This will help augment any existing vibration mitigating technology, to hopefully achieve a cumulative high level of protection.
- The design will be based on physical prototyping and testing, to ensure the design is rooted in practice rather than theory alone.
- It is important to explore underlying technology and specifically prove results in an experiment. Especially with regard to a startup, it will be useful to have realized tangible results within this thesis. This will help make the protection device a more credible proposition.
- If performing tests in a practical environment is not possible, testing will be done in a controlled environment instead.

3. Context analysis

3.2. Outline and magnitude

Hand-arm vibrations are an occupational hazard which can be caused by the use of power tools. The debilitating consequences of prolonged hand-arm vibration exposure are often hard to clearly identify. It often takes years of accumulated exposure to vibrations, after which injuries are hard to trace back to vibration exposure. This lack of identification might be one of the causes why hand-arm vibrations are still a hazard that is largely overlooked, and why in many countries exposure to vibrations is not a priority for the labor inspection to address.

3.2.1 Europe

Data gathered on European level (**Fout! Verwijzingsbron niet gevonden.** and **Fout! Verwijzingsbron niet gevonden.**) shows that exposure to vibrations in the workplace is a large issue, with roughly 1 in 3 workers of any profession being exposed to vibrations on a day to day basis. **Fout! Verwijzingsbron niet gevonden.** and **Fout! Verwijzingsbron niet gevonden.** show the vibration exposure per industry and country and include several forms of vibrations such as from, whole-body vibrations to vibrations from hand-held tools and stationary machines. However, these vibration sources are very different when it comes to possible consequences and solutions, and not separating the data by vibration source makes the data less useful. This indicates that, despite the fact that vibrations in the workplace is a large issue and that relevant data exists, the specific problem of hand-arm vibrations is still not well understood and prioritized within the government.

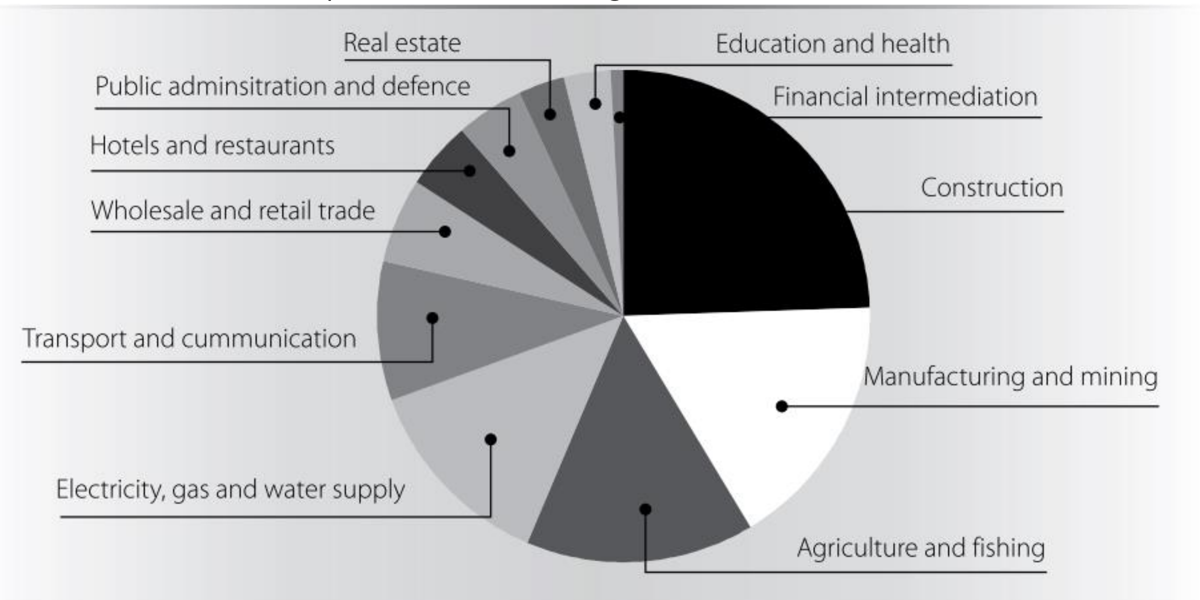
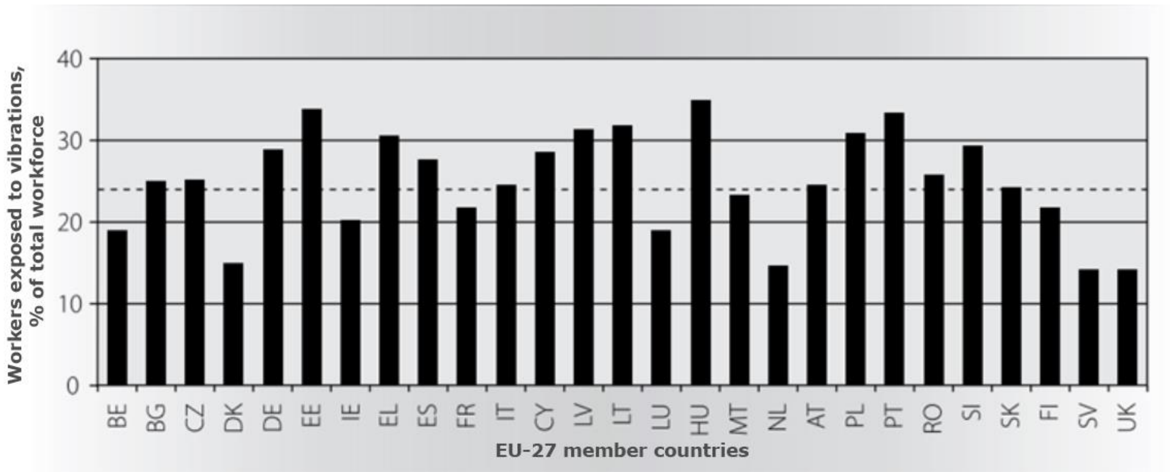


Figure 1: Occupational vibration exposure per industry. The construction industry accounts for 24% of total vibration exposure in the European workforce, where 63% of workers are exposed. Adapted from the European Agency for Safety and Health at Work report: "Workplace exposure to vibration in Europe: an expert review" [5].

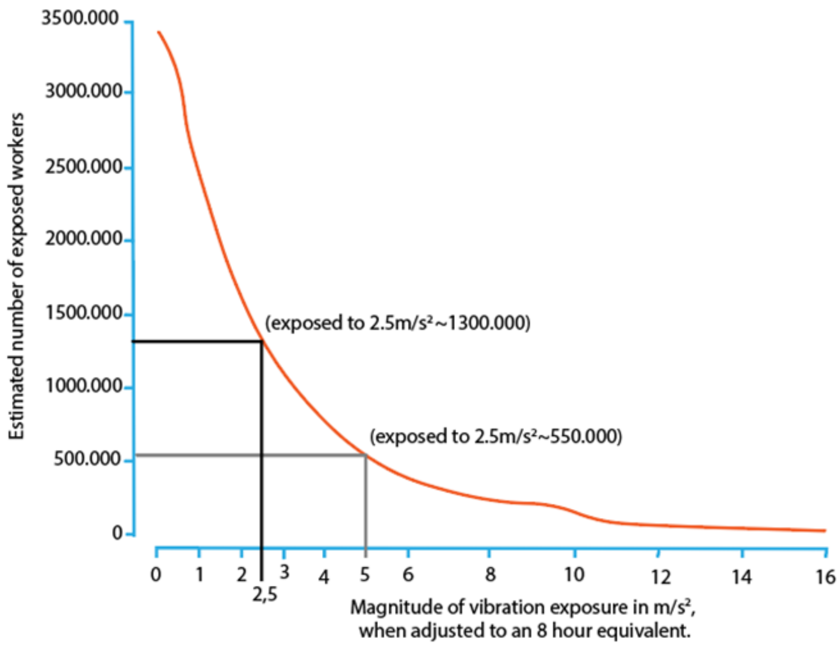


Figuur 2: Occupational vibration exposure per EU-27 country, as a percentage of the total workforce. Adapted from the European Agency for Safety and Health at Work report: "Workplace exposure to vibration in Europe: an expert review [5].

3.2.2 Hand-arm vibrations in the United Kingdom

A more adequate distinction between hand-arm vibrations and whole-body vibrations is sometimes offered by studies conducted in individual countries, presenting domestic statistics of the phenomena. As can be seen in **Fout! Verwijzingsbron niet gevonden.**, Britain is a prime example of this.

Since the '90s public attention has increased greatly for hand-arm vibrations in the UK. The Health and Safety Executive (HSE) reports over 2.000.000 workers being at risk for health issues as a consequence of hand-arm vibrations, with another 300.000 people already having developed severe symptoms which can be clustered under Hand-Arm Vibration Syndrome (HAVS)[6]. This could be a consequence of the fact that the UK historically had a large mining industry, where workers were exposed to long hours of breaking rock with heavy power tools.



Figuur 3: Shows the estimated number of exposed workers' (male only) according to the vibration magnitude. Highlighted are the number of workers exposed to 2.5m/s² and 5m/s². Adapted from The European vibration directive [7].

An indication of the British government recognizing HAVS as a serious health problem is the number and magnitude of compensations given to injured workers in the UK. In 1997 seven coalminers were compensated with £127.000 after having developed HAVS. Between then and 2004 over £100.000.000 has been given to HAVS injured coal miners. Another 7115 claims for HAVS have been appointed between 2008 and 2017 [8].

As the number of new cases has been declining since 2010, a hopeful indication is given that the British prevention initiatives are paying off (**Fout! Verwijzingsbron niet gevonden.**). Although, the HSE reiterates the fact that any data on hand-arm vibrations is likely to be an underestimation. The following reasons for this were identified:

- The worker does not know the cause of his injuries.
- The worker is aware of available medical or financial compensation for their injuries.
- HAVS cases are arising in other working contexts than expected

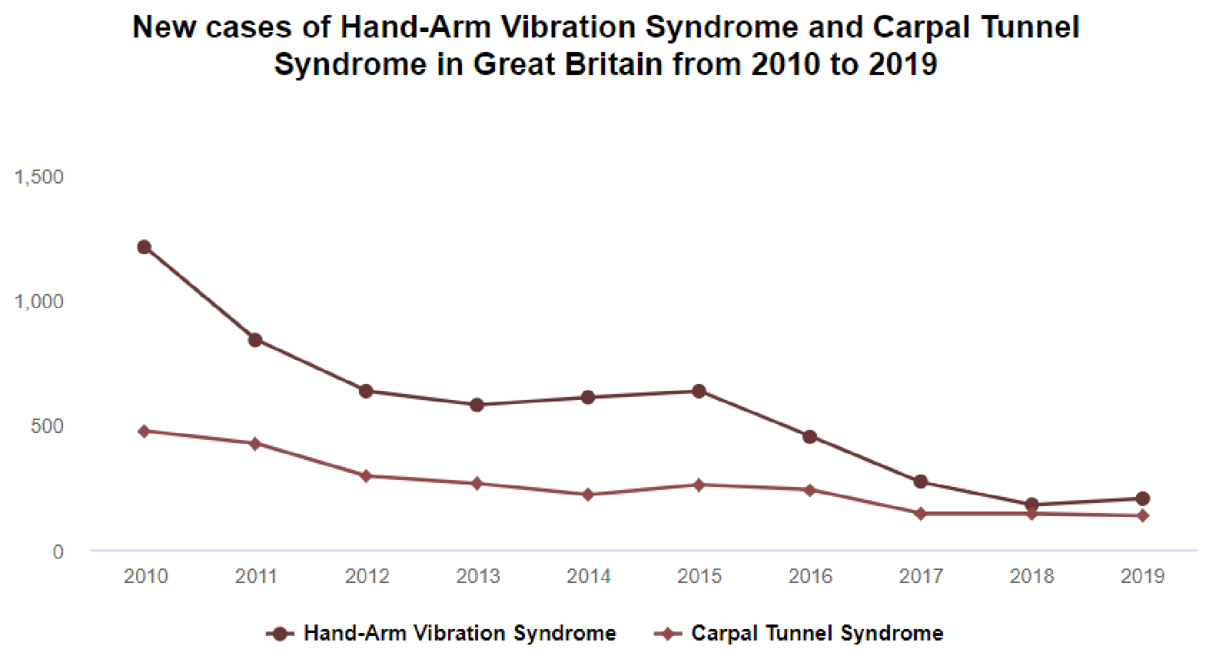
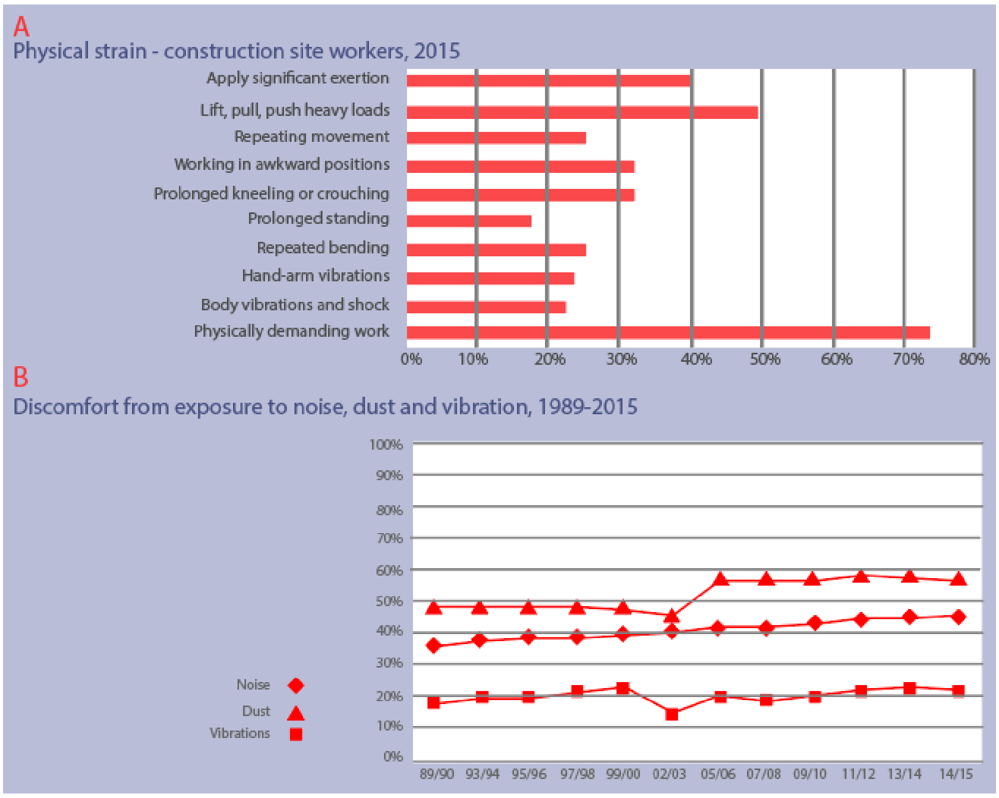


Figure 4: Cases of HAVs related diseases have been falling[9]

3.2.3 Hand-arm vibrations in the Netherlands

In the Netherlands much of the statistics are provided by Volandis, a research and consulting institute focused on the construction industry. According to Volandis, in the Dutch construction industry about 25.000 workers are exposed to hand-arm vibrations during their working day [10]. As shown in , a 2016 survey of 5000 construction workers reported that 24% of the construction site personnel reported being exposed to vibrations from power tools. In addition, around 20% of these workers reported discomfort from these vibrations. Although these numbers are not coming close to the percentage of cases reported in the more extensive research reports of the British data (**Fout! Verwijzingsbron niet gevonden.**), it does show that vibration exposure is also a problem in the Dutch construction industry. This discrepancy also suggests that the actual cases of HAVS are very likely underreported in the Netherlands.[11] Some figures have been found regarding professions in the Dutch construction industry and the corresponding vibration exposure, as seen in appendix 2.



Figuur 5: Main physical strains in construction work. Figure 5A 24% of construction site workers experience hand-arm vibrations and in figure 5B, 20% report discomfort as a result of vibrations. Construction industry report 2016.[11]

3.2.4 Conclusions

Based on research conducted by European Agency for Safety and Health at Work, Health and Safety Executive and Volandis, the following can be concluded:

- in some other EU countries better data is available on hand-arm vibrations than in the Netherlands, or the European Union as a whole. (recommendations);
- Hand-arm vibrations are a significant underestimated problem in the Dutch construction industry (recommendations);
- Hand-arm vibrations is a phenomenon spread across a multitude of professions within construction. (recommendations).

3.3 Work culture

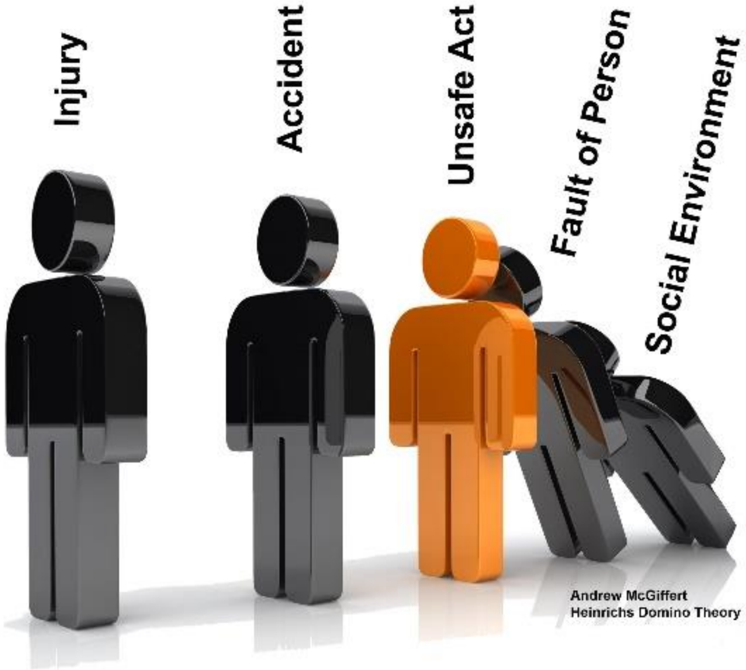
The construction industry is notorious for its safety issues, even in countries with high safety standards. Therefore, safety remains an ever-present issue. Generally speaking, in Europe the rate of fatal events in construction is 13 persons per 100.000, compared to 5 persons in 100.000 on average in other industries.[12] A contributing factor to an unsafe working environment is that workers are often reluctant to report their injuries. Often the ability to do jobs a certain way, and without complaint is part of the workers self-image, which can lead to workers not reporting their injuries or discomfort and as a consequence maintaining an unhealthy environment.[13]

A study including 135 American construction workers gave an overview why injuries are currently not being reported.[14] The main results can be found below:

- Perceived the injury to be too small. (72%)
- Accepted the pain being part of the job. (47%)
- Assuming home treatment might be sufficient. (47%)
- Unsure whether the symptoms are a consequence of the work activities. (36%)
- Afraid of not being re-hired after filing a complaint. (25%)
- Not being able to afford unpaid leave to visit doctor. (22%)
- Afraid of losing their job. (22%)

"When workers are expected to use a certain protection device, there is supervision on site to make sure that they in fact are made use of. So, in this sense the company has some control over their employees using protection gear. But workers in the construction industry can be conservative when it comes to their way of working. They can be reluctant to change their methods, and when it comes to doing their job, any protection gear that forms an impediment to getting the job done is often left aside. This way workers can sometimes make choices that are not in their best interest."

Wibo Feenstra – Safety expert [Appendix 1]



Figuur 6: The Heinrich domino theory, depicting the general preconditions that lead up to an injury.

3.3.1 Reacting to incidents

Construction companies seem to react to incidents in a reactive, rather than a pre-emptive manner. This can perhaps best be explained using the Heinrich Domino Theory, illustrated in Figure 6, which labels several layers of causation leading up to an accident [15]. The occurrence of an injury will incentivize a company to improve safety conditions. Hand-arm vibrations as a safety risk, are perhaps fundamentally different from other safety risks, as often no concrete incident occurs immediately leading to an injury. With hand-arm vibrations the more serious consequences, such as HAVS, develop over time making it rather hard to identify in-time. In case of preventing HAVS, an implicit strategy of reacting to incidents is not a suitable way of dealing with hand-arm vibration exposure.

3.3.2 Conclusions

From the consulted publications and the interview with Wibo Feenstra, the following can be concluded:

- Safety is a constant issue in construction. (*recommendations*);
- Workers can be reluctant to report their injuries. (*List of requirements*);
- Protection gear that poses an impediment to productivity tends to be left aside. (*List of requirements*);
- Construction companies and workers address safety issues in a reactive rather than pre-emptive manner. (*recommendations*)

3.4 Stakeholders

When considering the prevalence and impact of HAVS it can be concluded that many stakeholders are involved and affected. Therefore, it is important to consider all factors, views and consequences of hand arm vibration induced injuries. An overview of the current situation a worker faces when being exposed to hand-arm vibrations and its consequences is presented in figure 7. In this figure all the stakeholders are involved in a different way and in a different part of the worker's situation. In addition, in this section the stakeholders are all discussed individually.

3.4.1 SZW Inspectorate

It is the responsibility of SZW Inspectorate to enforce regulations and prevent injuries. However, situations with more immediate consequences (e.g. fall risk, life threatening injuries) are given higher priority than vibration exposure. SZW inspectors have very limited time to inspect a company making it difficult to assess any potential over-exposure to vibrations, as this is time dependent, and not directly visible. The declared vibration exposure in a power tool manual is usually the only way for an inspector to judge the safety of the working situation. In special cases the inspector can require the company to hire a specialist to do situation-specific measurements.[16]
Main stake: Enforcing regulations by inspecting companies as thoroughly as possible within the limited available time.

3.4.2 Construction company

The employer has an economic incentive to complete projects as cost effective as possible, which involves instructing their employees to use power tools for efficiency, often for extended periods of time. This can lead to violations of the regulations, as the maximum legal vibration exposure is relatively low, compared to the work that needs to be done. Overburdening the employee could result in paid sick leave and damage claims, a fine from the inspection, and additional delays on the work activities.
Main stake: Productivity without putting their workers at risk by exceeding the regulations.

3.4.3 Employees

Construction site workers earn their living by performing labor with their hands. They are at least to some degree judged on their productivity. Not reporting discomfort, injury, or hazards is often a part of their work culture, and by doing so avoid bringing their employment in jeopardy.
Losing sense of touch or the ability to exert force with their hands, as are known symptoms of HAVS, could potentially put them out of work, with little chance of retraining into another profession. At the same time, working with power tools under time pressure is part of their job, while the only effective measure against HAVS is limiting the time spent using the power tools.
In addition, their work injuries can diminish their quality of life by causing pain and reducing their ability to engage in leisure activities.
Main stake: continue doing their job without developing HAVS symptoms and risk of losing their job. and having no accumulated symptoms by the time they retire, while maintaining their quality of life.

3.4.4 Society & Healthcare

For society at large, HAVS is a health risk that could potentially be very costly. It can affect both young and older workers, In addition, it can cause workers to become rehabilitated for long periods of time, or even permanently, resulting in life-long social support provided by the tax payer.

Main stake: HAVS often results in life-long disability of young people, who need to be financially supported throughout their further lives, putting an immense financial strain on the tax payer.

3.4.5 Branch organizations (Bouwend Nederland)

A branch organization (e.g. Bouwend Nederland) exists to help improve the practices and professionalization of the construction industry. In addition, they promote collective research initiatives.

Main stake: Improving practices in the construction industry.

3.4.6 Worker/trade unions (FNV bouw)

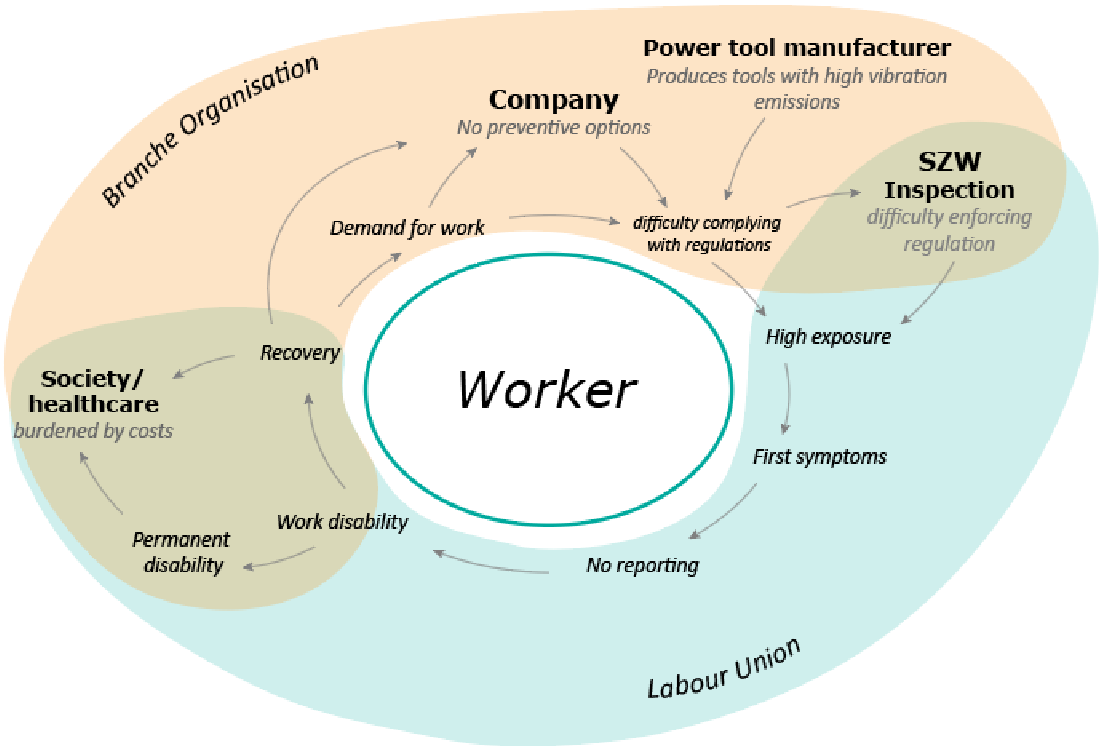
Negotiate on behalf of workers for better salary and benefits, as well as better working conditions. These unions could also help with promoting better safety practices, reasoned from a worker's perspective.

Main stake: Improving the working conditions and benefits.

3.4.7 Power tool manufacturer

Develops and produces the power tools needed in the construction industry. Some manufacturers do try to reduce the vibration emissions, but still most power tools still have too high vibration emissions.

Main stake: To keep market share in supplying the construction industry with power tools.



Figuur 7: A visualization of the hand-arm vibrations problem, centered around the worker. The labor union and branch organizations both exert influence on their respective sides of the situation. Noticeable is that all parties involved try to solve the problem in their own way, but none of these actions have enough effect to stop the cycle.

3.4.7 Conclusion:

HAVS is a persistent issue that results in workers becoming temporarily or permanently disabled. Even though each involved stakeholder seems to take mitigating actions against HAVS(as seen in **Fout! Verwijzingsbron niet gevonden.**), the problem still persists. Construction companies do try to protect their workers from over exposure, but have no viable means to do so. The SZW Inspectorate does try to enforce regulations as much as possible, but do not have the capacity to do so. Workers might want to report their discomfort and injuries but several factors (as discussed in chapter 3.3) dissuade them from doing so. The healthcare system rehabilitates workers afflicted by HAVS but is unable in to completely remedy severe cases. Meanwhile, the branch organizations stimulate knowhow and research for better practices, and the labor unions advocates for better working conditions overall. However, just like the SZW Inspectorate, neither seems to have HAVS prevention as a high priority.

It seems that the crux of the problem lies in a tension that exists between the demand for work and the ability to comply with regulations. The industry demands a certain productivity that is simply incompatible with a healthy work environment when it comes to hand-arm vibrations.

From analyzing the relevant stakeholders and their relations the following can be concluded:

- Hand-arm vibrations is a problem that greatly burdens the healthcare system and therefor society. (recommendations);
- It is difficult for workers to avoid being afflicted by HAVS. (recommendations);
- No individual stakeholder has the ability to solve the problem of Hand-arm vibrations. (recommendations);

3.5 Rules and regulations

The main regulation concerning hand-arm vibrations, as stated in the European Directive 2002/44/EC (2002) dictates the following:

- An action value of 2.5m/s^2 at which the employer needs to take preventive measures;
- A stopping value of 5.0m/s^2 that may not be exceeded In any case [17].

These values apply to an 8-hour workday. As illustrated in **Fout! Verwijzingsbron niet gevonden.**, for any vibration emission level an equivalent exposure can be calculated, which determines the maximum time of allowed exposure. For example: A power tool with a 5.0m/s^2 emission can be used for two hours to comply with the action value, and 7m/s^2 emission for only 30 min.

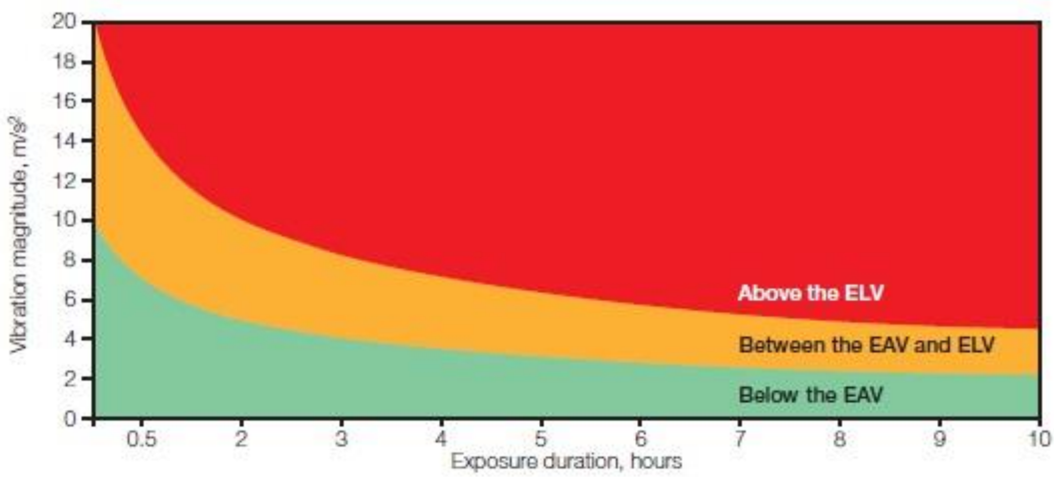


Figure 8: The action value and the stopping value (in the graph Exposure Action Value(EAV) and Exposure Limit Value (ELV)) illustrated in a graph with respect to exposure time.

3.5.1 Dutch inspection

The SZW Inspectorate is priority driven, meaning that inspectors will tend to look at top priority concerns while inspecting companies. This usually means focusing at risk of falling, and other hazards leading to an immediate injury or life threating situations.

3.5.2 Inspections in practice

To identify whether workers are exceeding the safety limits, inspectors often carry a chart, to easily identify tools with high vibration emissions (see appendix 4). Performing a proper vibration measurement is difficult, and the inspector has no choice but to take the declared vibration emission of the power tool in question as stated by the manufacturer in the manual. The inspector can in some cases request the company to hire an expert to perform a vibration measurement in a particular work situation (see appendix 3).

When projecting the safety limits on this chart (see appendix 4) it can easily be concluded that the exposure limit (i.e. 2.5m/s^2) is easily reached. This makes the compliance to the regulations very difficult for companies (for an anecdotal example the reader is referred to appendix 1).

For an inspector, it is difficult to determine how long a worker has been using a certain tool, and even more difficult to conclude anything about his work pattern over a longer period of time. Creating more insight into this aspect would therefore be of great use to the SZW inspectorate. When companies have data on their vibration emissions, the inspector has the means to objectively judge the situation [16].

> *"When an inspector visits a company, the entire inspection usually has to be done within an hour. This means that there is not much time available to focus on one particular situation, and more imminent hazards will get priority.*
>
> *When a violation of vibration exposure limits is determined, one of two things can happen. In case of exceeding the stopping value, the inspector will require the company to cease the work activity on the spot, and a fine is given. The work activity can only be recontinued when the company can prove that the exposure limit is no longer exceeded to an inspector after a certain period. Continuing the activity regardless is considered a criminal offence. In case of exceeding the action value, the work may be continued but the inspector will demand a change of the work situation within a given time. This can involve purchasing a protection device."*[16]
>
> Maroesja Bonsen – SZW inspection

3.5.3 Rules for manufacturers

The European Machinery Directive (2006/42/EG) compels tool manufacturers to minimize the vibration emissions in their products, particularly at the vibration source.[18] Manufactures need to disclose these values based on testing according to ISO 20643. The construction companies in turn need to carry out a risk-assessment concerning each work activity involving the power tool.

3.5.4 Rules for Personal Protection Equipment (PPE)

PPE's are only allowed when these comply with the regulations as mentioned in Regulation (EU) 2016/ 425[19]. This regulation does mention vibration protection in particular, but does not demand any far-reaching conditions. In addition, it acknowledges that a PPE alone cannot be sufficient to comply with the regulations on vibration exposure.

> *"As regards mechanical vibrations, it is appropriate to remove the requirement not to exceed the limit values set by Union legislation on the exposure of workers to vibrations since the use of PPE alone is not able to achieve this objective."*
>
> Amendment 22, Regulation (EU) 2016/ 425[19]

One important consideration the EU regulation on PPE's does mention is the need to specifically address the particular components of the vibration that are especially harmful to the exposed body part.

> *"PPE designed to prevent the effects of mechanical vibrations must be capable of ensuring adequate attenuation of harmful vibration components for the part of the body at risk."*
>
> Article 3.1.3. Regulation (EU) 2016/ 425[19]

Particular to anti-vibration gloves there is ISO 10819[20], which states that the glove:

- Must transmit no more than 90% of the frequencies between 25 and 200 Hz.

- Must transmit no more than 60% of the frequencies between 200 and 1250 Hz.
- Must not exceed a thickness of 8mm.
- Must cover the whole hand and fingers.

3.5.5 Conclusions

From the findings described in this chapter, the following can be concluded:

- Workers may be exposed to a maximum of $2.5m/s^2$ per 8 hours of work. (*Program of requirements*);
- The SZW Inspectorate has several other safety hazards as a higher priority than hand-arm vibrations. (*Recommendations*);
- The regulation values of $2.5m/s^2$ and $5.0m/s^2$ are very low values compared to the average vibrations generated by the tools, making it is very difficult not to exceed these thresholds. (*Recommendations*);
- It is difficult for an inspector to determine the duration a worker has been working with a given tool. (*Program of requirements*);
- The SZW Inspectorate could benefit greatly from data collection on hand-arm vibrations exposure. (*Program of requirements*);
- Any personal protection equipment aimed at vibrations must in particular address the vibration component harmful to the exposed body parts. (*Program of requirements*);
- Any vibration glove must at most transmit 90% of the frequencies between 25 and 200 Hz, and no more than 60% between 200 and 1250 Hz. (*Program of requirements*);
- Vibration gloves must not exceed a thickness of 8mm. (*Recommendations*);
- Vibration glove must cover the whole hand and fingers. (*Recommendations*);

3.6 Power tools and their use

In the construction industry workers are exposed to hand-arm vibrations in a myriad situation, depending on the power tool used and the work activity performed. All these different situations pose different vibration emissions on the worker, and have a different corresponding exposure time according to the regulations.

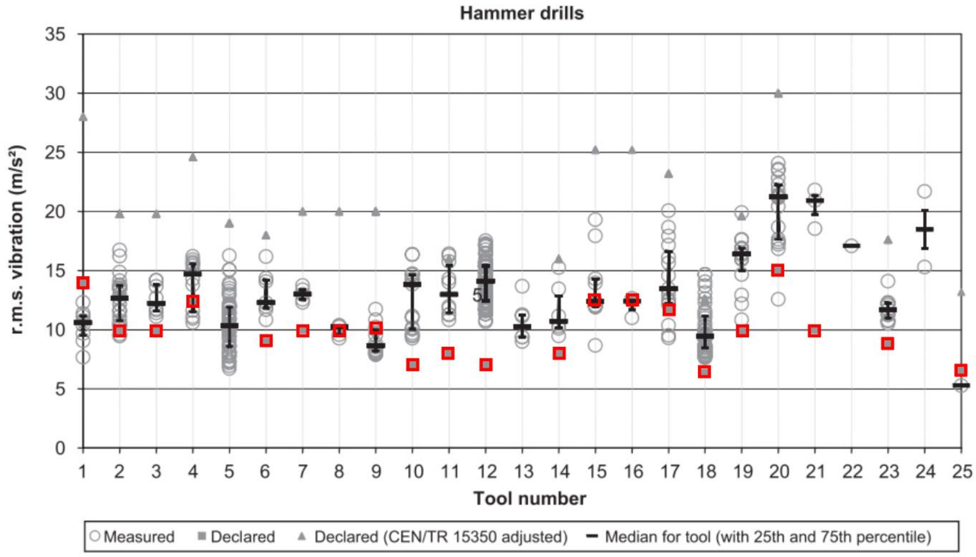
3.6.1 Common power tools and their vibration exposure

Rimell et al.[21] offers an insight into the range of tools and vibration exposures one might encounter on a typical construction site. In table 1 shows a representative collection of archetypical tools, with their corresponding vibration emissions declared by the manufacturer, and actual emissions measured in a lab environment.

Tabel 1: Tool archetypes and their specifications.

Power tool	Grip	Declared emission	Maximum duration of use (action value)	Measured emissions	Maximum duration of use (action value)
Angle grinder	straight grip	2,5 m/s^2	8h	4-11 m/s^2	3h 8min - 1h 39min
Stone Saw	pistol grip	4-8 m/s^2	3h 8min - 47 min	3-9 m/s^2	5h 33min - 47min
Belt Sander	pistol grip	2-9 m/s^2	12h 30 min - 37min	2-9 m/s^2	12h 30 min- 37min
Battery drill	pistol grip	2,5-17 m/s^2	8h - 10min	4-21 m/s^2	3h - 8min
Reciprocating saw	pistol grip	2,5-17 m/s^2	8h - 10min	2-28m/s^2	12h 30 min - 4 min
Hammer drills	pistol grip	6-15 m/s^2	1h 23 min - 13min	5,5-24 m/s^2	1h 39min - 5 min
Breakers	two handed	3-15.5 m/s^2	5h 33min - 12min	4-24 m/s^2	3h 8min- 5 min

When comparing the declared to the actual emissions, it is clear that the vibration emissions declared by the tool manufacturers often show an underestimation of the actual exposure. An extensive example of this is shown in figure 9, where vibration data on multiple models of the hammer drill archetype show considerable deviation from the declared value. Especially when expressed in work time this difference becomes very clear (table 1). In one example a breaker has a declared emission of 8 m/s^2 and a measured vibration of 24 m/s^2. This results in a considerable difference of safe usage time per day (47 min and 5 respectively, as can be seen using figure 8).[21]

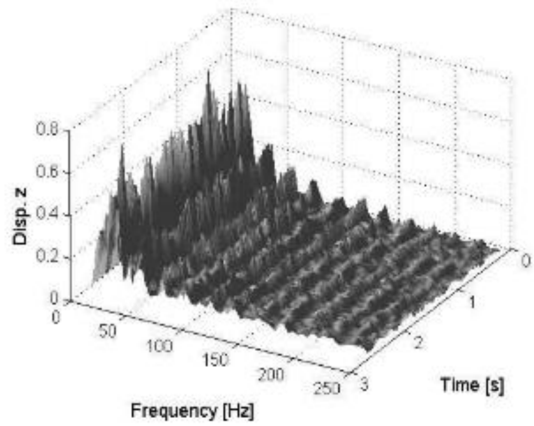


Figuur 9: Variations in declared(red) and actual vibrations that exist in just one type of power tool. Factors such as wear on the mechanism and different tool bit inserts can influence the vibration emissions. In most cases the declared emission is a significant underestimation of the true vibration emission. Many factors can influence the actual emission, different from the declared emission, specific to each individual case.[21]

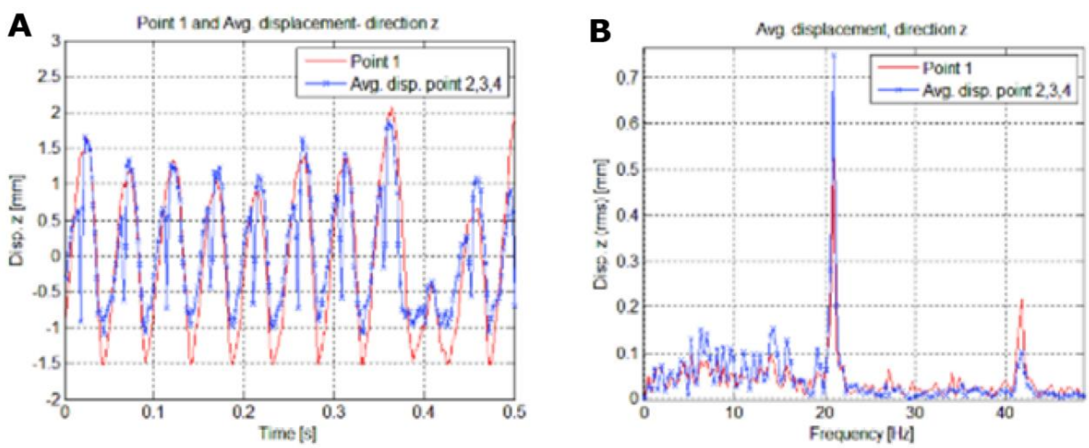
3.6.2 Measuring vibrations

The vibrations emitted by a power tool are complex. There are three dimensions to consider, each comprising of its own range of frequencies. Simplification of the measured vibration is almost always necessary. and Figure 11 show the measured vibration of a demolition hammer, where displacement in one direction (z-axis), and its main frequencies (up to 250Hz) are plotted respectively.

As can be seen in and 11B the vibrations of a percussive power tool, such as a demolition hammer or hammer drill, typically consist of frequencies below 50 Hz. [22]



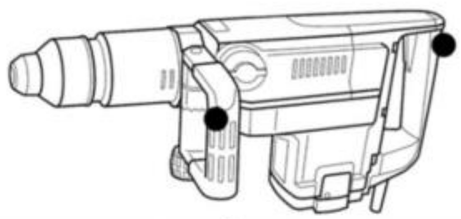
Figuur 10: A one-axis measurement of a power tool across frequencies 0-250Hz, over 3 seconds.



Figuur 11 A and B. 10A shows displacement over time, the actual vibration. 10B Shows the frequencies from 0 to 50 Hz.[18]

3.6.3 Project focus: The hammer drill

The hammer drill is used to drill holes in concrete or to remove concrete by chiseling. This tool is often used on shoulder height and pressed against a wall, upward against the wall, or downwards into the ground. The tool is held with both hands, one in 'pistol grip' exerting force on the back and one guiding and supporting the weight of the tool form a handle bar in the middle of the tool (figure 12). The worker often leans into the tool to exert more force on the tool, depending on the work piece this can be forward or stooped in downward direction. Appendix 5 shows an extensive analysis of several archetypical tools represented by Rimell et al.



declared emission	6-15 m/s^2
measured emission	5,5-24 m/s^2

Figuur 12: Case description of the hammer drill with an example of use and its declared and measured vibration emissions.

To simplify the research, but yet have a design which is compliant with several power tools, the hammer drill configuration with pistol grip is used as a focus point for the design of a damping solution in this thesis. The hammer drill itself is a tool that has a relatively high vibration emission. Its pistol grip and two-handed configuration appears to be common across most power tools (table 1).

Specializing on a percussive tool such as a hammer drill is also an advantage as percussive tools overall tend to have the highest emission rates of all power tools and have similar frequency profiles. In this way the solution for one percussive tool is likely to be applicable or easy to adjust to the frequency profiles of other percussive tools, making one solution possibly effective for several tools.

3.6.4 Conclusion

From this analysis on various power tools and their properties, the following can be concluded:

- A very diverse range of power tools is used in the construction industry. (*Program of requirements*);
- Within a single type of tool there is much variation in vibration emissions, depending on situation dependent factors. (*Program of requirements*);
- Vibrations within a single measurement are a complex combination of frequencies in x y and z directions. (*recommendations*);
- Percussive power tools emit frequencies mainly below 50Hz. (*Program of requirements /recommendations*);
  The hammer drill can be taken as a design focus, as it is comparable to a large variety of tools. (*Program of requirements*);

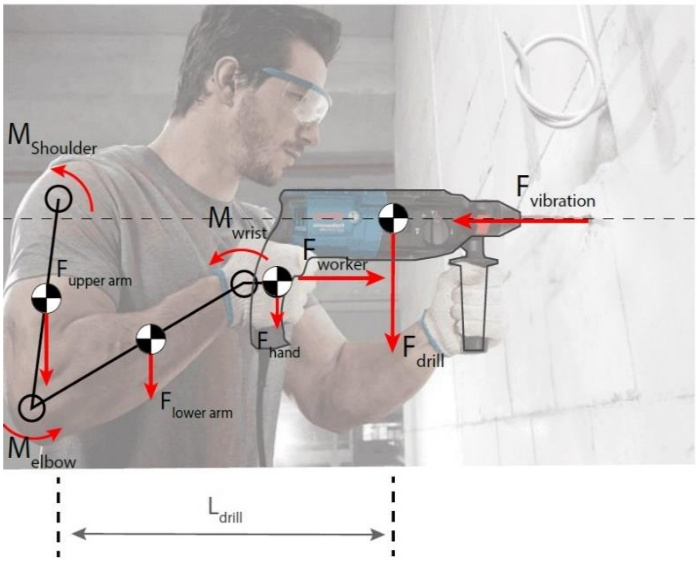
3.7 Biomechanics

3.7.1 Upper limb analysis

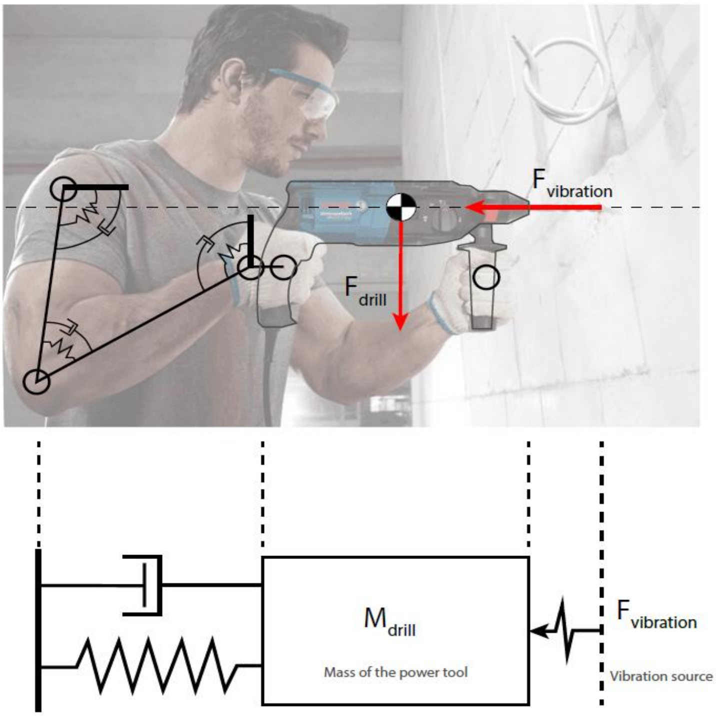
It is worth taking a closer look at the biomechanics of operating a hammer drill, as this can give valuable insight into what forces are at play and why. For simplicity of the illustration, only the right-hand arm is considered in this analysis.

When operating the power tool(Figure 13), the construction worker needs to position and hold the power tool in the desired position and direction. This means countering the weight of the limbs ($F_{upper\ arm}$, $F_{lower\ arm}$, F_{hand}) and the weight of the tool(F_{drill}). Of these forces, F_{drill} is most significant as it is multiplied by L_{drill}. This means and extended arm will require more exertion. Additionally, the worker exerts a force along the centerline of the tool, driving the drill into the wall(F_{worker}).
These actions result in tensioning the muscles in the shoulder, upper and lower arm, needed to exert this moment in each rotation point ($M_{shoulder}$, M_{elbow}, M_{wrist}).

The hand presses into the grip while operating, often using the bodyweight to lean into the power tool. The body of the worker is mostly isolated from the vibrations due to the arm acting like a spring-damper. The more the muscles are contracted, the further vibrations will propagate through the arm, and into the shoulder. More precisely: contracting the muscles makes the arm behave like a stiffer spring, leading to higher frequencies of vibration reaching the body.



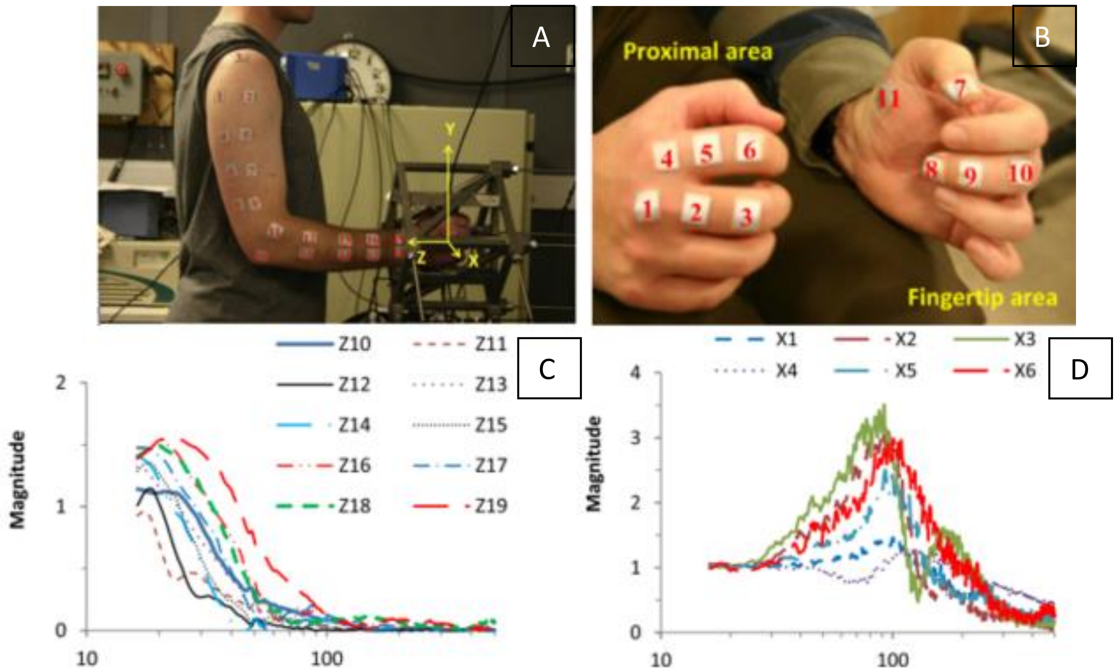
Figuur 13: Biomechanical analysis: Exerting moment by the limbs.



Figuur 14: Biomechanical analysis: The cumulative hand-arm system as a spring-damper system.

3.7.2 Vibration propagation through the arm

According to their frequency, vibration propagate differently through the human body. Generally speaking, lower vibrations travel further into the body. Welcome et al. (2004) examines this phenomenon in detail and concludes that higher frequencies are measured in the fingers and hand (figure 13B/D), and lower frequencies are measured in the lower and upper arm (figure 13A/C).



Figuur 15A B C and D: A and C show frequencies measured in the arm, having an increased magnitude from 18-45 Hz. Figure B and D show the measured frequencies in the fingers, which have an increased magnitude from 25 to 220 Hz.

3.7.3 Function analysis

Using the biodynamic analysis in chapter 3.7.1, the various subfunctions can be identified. These are listed in the table 2. It can be concluded that both handling and actively operating a hammer drill involves substantial contraction of the muscles in the shoulder arm and hand. The hand, and there by also the muscles in the lower arm, are under tension, simply by holding the power tool. The muscles in the upper arm and the shoulder are in turn exerted by holding the weight of the arm and tool upright and partially extended from the body. When operating the power tool, the arm and shoulder muscles are exerted further, by pressing the tool along its centerline into the wall.

Tabel 2: Function analysis of the hand and arms.

Limb	Subfunction	Action
Right hand (total)	Hold (make connection)	grab / clamp down
Wrist	Hold tool upright	Exert moment on handle
Finger	Engage/disengage	Press down on trigger
Thumb	Secondary control	Press down on button
Arm	Exert pressure	extend arm
Right arm	Absorb vibration	flex muscles
	Determine distance	extend / retract arm
Left arm	Aim tool (direction of centerline)	position left and right hand in relation to each other
	Support weight of tool	exert moment

3.7.4 Conclusion

Considering the findings from the mentioned publications and from the biomechanical analysis, the following can be concluded.

- Operating a hammer drill itself requires contraction in the whole arm and shoulder as well as significant clenching of the hand. (*Program of requirements*);
- Contracting muscles in the hand-arm system causes vibrations to propagate further up the arm. (*Program of requirements*);
- The subfunctions of holding (making connection) and holding the tool upright are important to distinguish. (*Program of requirements*).

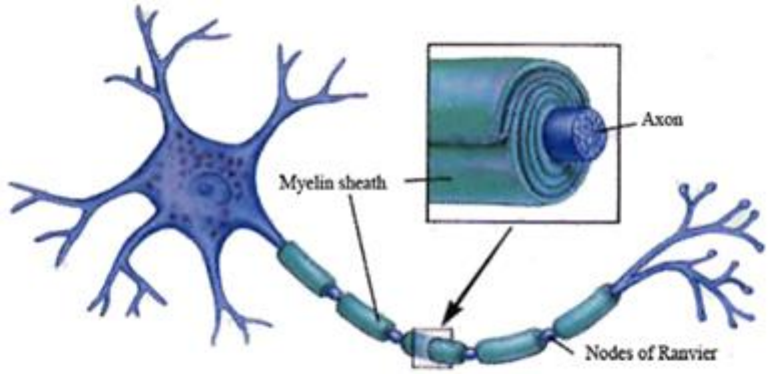
3.8 Medical consequences of hand-arm vibrations

Exposure to vibrations from power tools can introduce changes to the nerves, arteries, muscles and bones (muscular skeletal system) in the affected area. When these changes are a consequence from vibration exposure to the upper extremities, this is collectively defined as hand-arm-vibration-syndrome (HAVS). Of these medical conditions, especially the nerves and arteries are affected. In contrast to the muscular-skeletal system, where no serious injuries are reported, literature is limited.

3.8.1 Neurological

The exact way in which vibrations cause nerve damage is not fully understood. Demyelination (destruction of myelin) might be the primary cause of vibration induced neuropathy (dysfunction of one or more peripheral nerves, typically causing numbness or weakness). Myelin sheets wrap around the axons, which are the links nerves are comprised of (figure 16). These myelin sheets protect the axon and make nerve signals travel faster over the axon. Vibrations can cause these sheets to unravel and leave the axons unprotected, in some cases causing them to die off [23].

Another phenomenon that has been observed in skin specimens of patients with HAVS, and in particular patients with a symptom called Vibration White Fingers (VWF), is thick perineurial fibrosis: scar tissue forming around the nerves. This indicates that vibrations can cause perineurial edema, a build-up of fluid around the nerve, followed by a thickening of scar tissue around the nerve, and eventually diminishing of the nerve fibers themselves [24].



Figuur 16: The Axon covered by Myelin sheaths.

3.8.2 Vascular

On the level of the arteries the most prominent symptom of HAVS is (Vibration White Fingers) VWF, also know a secondary Raynauds Phenomenon. In VWF the digital arteries undergo a vasospastic reaction, as seen in figure 17 [25] and 18 [26]. Vasospastic reaction is the ability of the arteries to reduce their circumduction and thereby narrowing and reducing the amount of blood supply. This reaction is essential in governing for instance the temperature regulation of the extremities. However, this reaction can also be pathological after the hands and arms are regularly exposed by vibrations, which could eventually lead to a permanent vasospastic reaction. This results in the fingers having a shortage of blood, in severe cases leading to severe vascular damage at the smallest of arteries: the capillaries. Unfortunately, the monitoring and diagnosis of capillary damage is complicated due to the fact that capillaries are extremely small (1 blood cell wide) and are dispersed throughout the skin and muscles [27].

Figuur 18: Raynaud's Phenomenon is caused by constriction of the blood vessels.

Figuur 17: A manifestation of Raynaud's Phenomenon.

Vibration reduces the blood flow in the directly, and indirectly exposed fingers. In addition to the effect on blood vessels caused by vibration exposure, exerting force with the fingers can also reduce blood flow significantly [28].

3.8.4 Pathology

In pathological terms, the neurological consequences of HAVS result in a loss of sensory function, reduced grip force, and in severe cases loss of motor function. Carpal tunnel syndrome is also an associated consequence, but is difficult to diagnose as a vibration related injury. The vascular consequences manifest themselves in blanching of the fingers, especially in combination with cold environments. Prolonged exposure can result in reduction of the number of capillary arteries, and the overall innervation of the hands.

> *"Early symptoms of Hand Arm Vibration Syndrome include the sensation of tingling, and muscle cramping in the fingers. This is possibly caused by a reduced ability of the blood to remove waste substances from the muscles due to the reduced blood flow. In general vibration exposure increases muscle tension throughout the whole body. When vibration exposure is resumed, symptoms will start to return earlier each time. In some cases, within a week. "*
> Roelie Knoops – Ergonomics expert

3.8.5 Conclusion

Considering these findings regarding the medical consequences of hand-arm vibrations the following can be concluded.

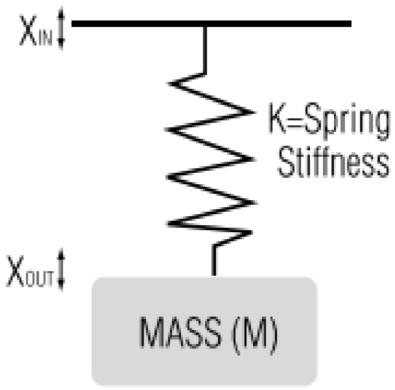
- Prolonged vibration exposure causes neurological and vascular diseases. (*recommendations*)
- Returning to working with hand-held power tools after recovery quickly brings back symptoms. (*recommendations*)
- Exerting force with the fingers reduces blood flow in the fingers. *(Program of requirements)*

3.9 Mitigating Vibrations

In developing a protection device against vibrations, it is important to understand how vibrations exactly work. This paragraph will discuss the relevant theory and technologies associated with vibrations.

3.9.1 Vibration theory

A vibration is a repetitive motion depending on two elements: a weight and a spring (as seen in figure 19). When the weigh is put into motion, the system continuously transfers its energy from stored potential energy in the spring (at its maximum amplitude), to kinetic energy in the weight. In reality, any object, be it part of a machine or human body, has these two properties to some degree. The relation between the stiffness and weight of an object determines its natural frequency. When an input vibration approaches this natural frequency, the vibration energy will accumulate, causing the mass to oscillate with an increasing amplitude. Subsequently, an opposite vibration of that same frequency will take energy away from the system, decreasing the amplitude.



Figuur 19: A spring weight system in its simplest form

3.9.1.1 Complex vibration

As seen in chapter 3.6.1, vibrations emitted by power tools are much more complex. This is true for almost all physical vibrations measured in reality. The simple sine-form as seen in theory, is simply the vibration of a single isolated phenomenon, in this case occurring somewhere in a power tool. All these vibrations combined result in a complex vibration, as seen in **Fout! Verwijzingsbron niet gevonden.** [29]. This complex vibration looks much more chaotic than the individual parts would suggest in the first place.

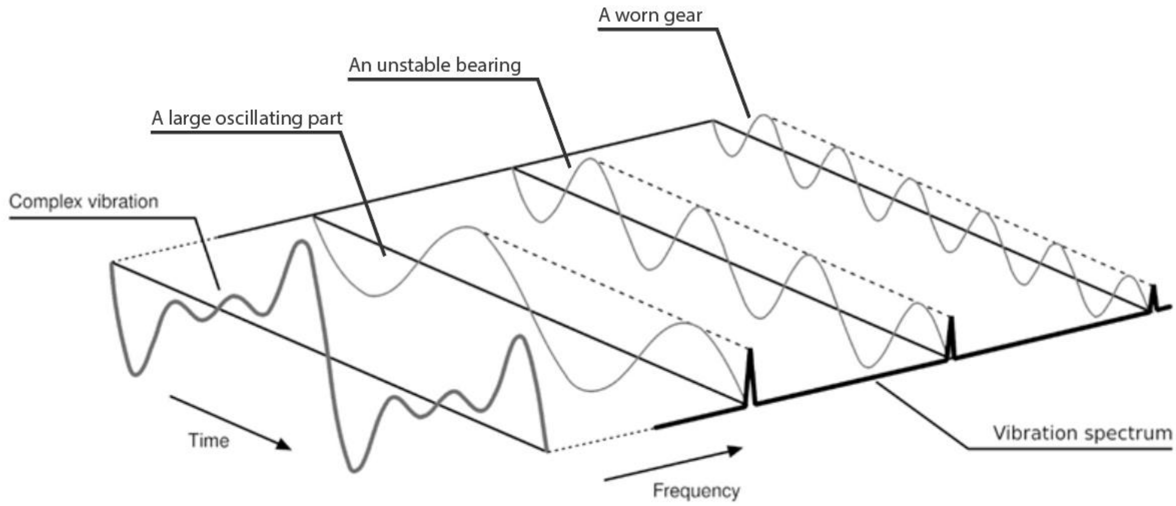


Figure 20: An illustration of how vibrations of various origins in a power tool can combine to form a complex vibration.

3.9.2 Basic technologies for vibration isolation

When designing a vibration mitigating product, it is important to understand the basic principles of vibration mitigating methods. These principles will be explained in this paragraph, with an emphasis on elastomer barriers.

3.9.2.1 vibration damping by elastomer barrier

A simple and effective method of isolating an object from vibrations is using an elastomer mount between the object and vibration source [30]. A flexible material, usually rubber, provides the needed support or mechanical connection, but can deform enough to absorb vibrations to some degree.

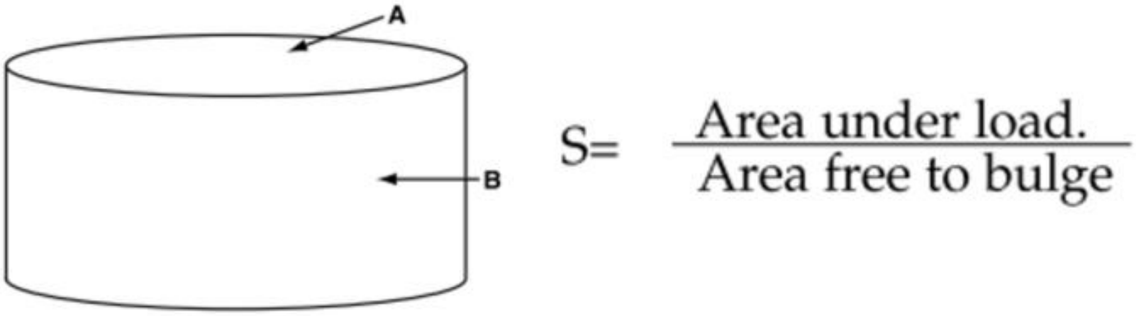


Figure 21: The stiffness of a barrier as a result of its geometry (S), is determined by the relation between the area under load and the area free to bulge.

The vibration absorbing properties of the elastomer barrier are determined by its material properties and its geometry. When the barrier is deformed, the material behaves like an incompressible solid. Therefore, the ratio between the area under load and the area that can bulge outward is an important factor (**Fout! Verwijzingsbron niet gevonden.**) [30]. Together with the material properties, this ratio determines how easily the elastomer barrier can deform, and by doing so, absorb vibration. A thin and wide barrier will not absorb much vibration, while a thick and narrow barrier will.

An elastomer barrier has the property of absorbing higher frequencies, but amplifying lower frequencies near its own natural frequency. Figure 22 shows this effect in more detail [30]. The effective isolation region, where the transmissibility factor is negative, is a multiple of the barriers resonance frequency. A good vibration isolator will therefore have a natural frequency more than four times lower than its targeted vibration frequency. When dealing with a range of frequencies, as is the case with a power tool, Some of the lower frequencies will inevitably fall within the amplification region. A low natural frequency of the isolator is thus desirable.

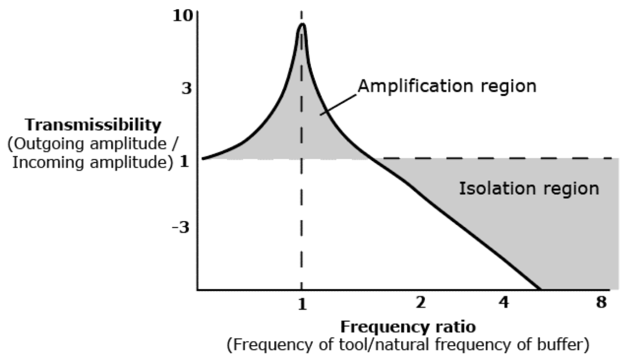
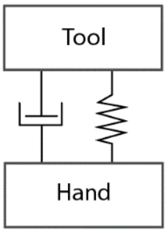


Figure 22: transmissibility versus frequency. On the X-axis: the ratio between the target frequency and the natural frequency of the elastomer barrier. On the Y-axis: The transmissibility factor. a factor of more than 1 means the barrier amplifies the vibration. A negative factor means the vibration is reduced. A material will magnify a vibration around its resonance frequency(1), and will diminish the vibration past a certain ratio of its resonance frequency. This is called the isolation region.

3.9.2.2 Passive System

A passive system is a vibration barrier with no control elements (figure 23), that can be tuned to fit its application. It will absorb a vibration near its natural frequency, but cannot adjust when the input vibration changes. The barrier can be a literal spring and damper, or a elastomer damper as discussed in 3.9.2.1.

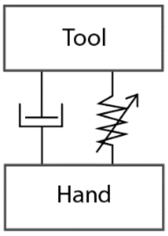


Figuur 23: A passive system

Pro's	Con's
• Very simple • No actuators needed	• Effectiveness can be limited. • Not adaptable to changing vibration.

3.9.2.2 Semi-active System

A semi-active system has an actuator that changes the properties of the spring-damper, changing the pretension for example (figure 24). This effectively changes its natural frequency, making it able to adapt to any input vibration.



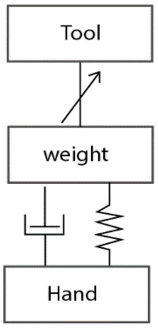
Figuur 24: A semi-active system.

Pro's	Con's
• Reasonably simple Can adapt to changing vibrations	• Limited adaptability

3.9.2.3 Active system

An active system has an actuator that creates a vibration. With a powerful enough control system, it can mirror the input vibration exactly and generate an anti-vibration (figure 25). This can result in near zero amplitude, so no residual vibration reaching the hand.

Pro's	Con's
• Potentially very effective • Can adapt to changing vibrations	• Complex • Difficult to develop



Figuur 25: An active system

3.10 Mitigating vibrations in practice

There are several options of reducing vibration exposure for workers and employers to be considered. Several protection devices are available on the market, and several strategies are recommended by the SZW Inspectorate. To put these options into perspective, they are order according to the Hierarchy of Controls in Figure 26.

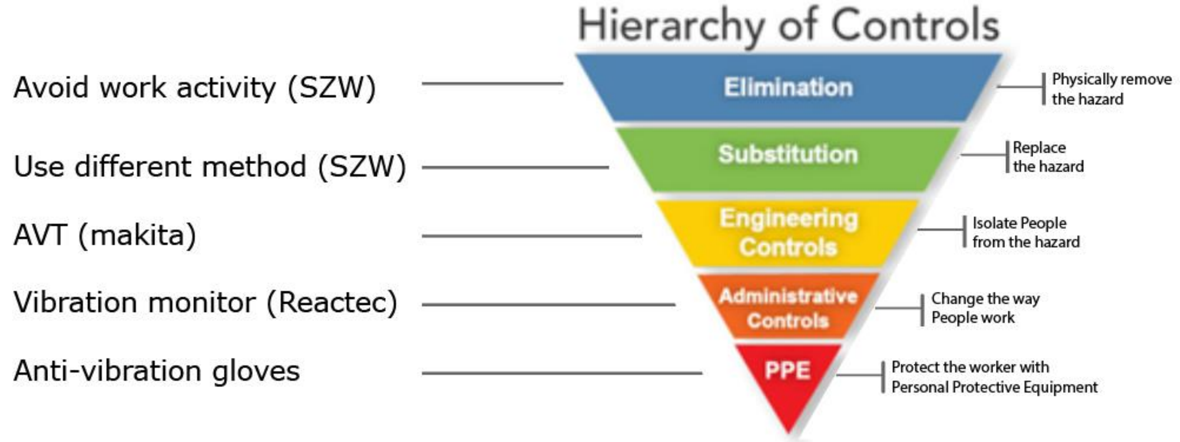


Figure 26: The Hierarchy of controls shows the preferability of safety measures according to their category. Safety measures related to hand-arm vibrations are added (on the left) for context.

In addition, the SZW Inspectorate defines anti-vibration gloves as PPE's (Personal protection equipment). Which classifies them as a so called 'last resort' protection measure [16]. This view is corroborated by Hewitt and colleagues stating:

> "*Ultimately, anti-vibration gloves cannot be relied on to provide sufficient and consistent protection to the wearer and before their use is contemplated all other available means of vibration control ought first to be implemented.*"- Hewitt et al. 2016

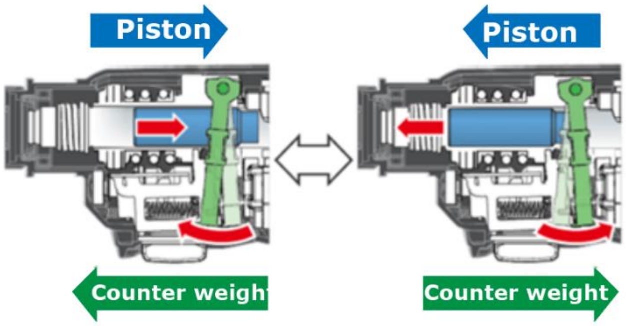
3.10.1 Integrated vibration reduction within power tool

Power tool manufacturers have picked up on the problem of hand-arm vibrations and have implemented several vibration reducing improvements within their products. A good example is power tool manufacturer Makita, with their AVT (antivibration technology) product line [31]. This is a collection of mechanical measures implemented within their power tools that are aimed at reducing vibrations. The three archetypical forms of vibration dampening techniques implemented in this line are: the use of a counterweight, a spring damper and vibration dampening handles.

In AVT, 'active' is presumably meant in the sense that the counter vibration is powered, just like the source vibration. In contrast to what active vibration usually means, a control system adjusting the counter vibration to the vibration picked up by the sensors.

3.10.1.1 Internal counter-weight.

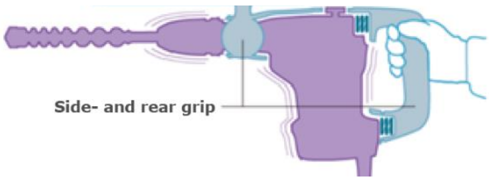
As shown in Figure 27, a weight is actuated in opposite direction to the functional part of the device, essentially reducing the net disbalance in the machine.



Figuur 27: An internal counter-weight, a part of the AVT product line. The counterweight causes an oscillation counter to the working component of the power tool.

3.10.1.2 Vibration isolated grip

As shown in Figure 28, this measure means a passive damper has been added between the vibration source and the user. In the case of disk cutters, the handles are padded with an elastomer material.



Figuur 28: A vibration isolated grip, integrated in a power tool.

3.10.1.2 Anti vibration technology comparison

When comparing the declared emissions of these power tools and the emissions found in **Fout! Verwijzingsbron niet gevonden.** in chapter 3.6.1, the AVT technology does not seem to have a significant impact (**Fout! Verwijzingsbron niet gevonden.**).

Tabel 3: A comparison between declared vibration emissions of AVT tools, and their common equivalent.

Power tool with AVT	Declared (AVT)	Declared (reference)
230 V hammer drill	7,0 m/s^2 [32]	6-15 m/s^2 [21]
230 V reciprocating saw	9,5-10,5 m/s^2 [33]	2,5-17 m/s^2 [21]
230 V breaker	6,5 m/s^2 [34]	3-15.5 m/s^2 [21]

The declared emissions are still within the same range as other tools in their category, albeit at the lower end of that range.

pro’s	con’s
Most practical solution for the worker.	Effectiveness is limited.

3.10.2 Anti-vibration gloves

Anti-vibration gloves, as seen in figure 29 [35], are gloves with at thickened layer of a rubber or foam-like material that offer a vibration damping barrier between the hand of the user and the power tool handle. The vibration damping properties are determined by the thickness and the material properties used. Currently anti-vibration gloves are the only wide spread personal protection product implemented in daily construction work. The anti-vibration gloves are often proposed as a fix-all solution for HAVs, but in practice are not as effective as suggested. These anti-vibration gloves can reduce exposure to high frequencies

Figuur 29: A common type of anti-vibration glove, with padding across the palm and fingers.

(>500 Hz) but are overall not effective. For comparison: most emissions of power tools stay within the 10-200Hz range, which thus cannot be dampened effectively by these gloves [4]. With regard to low frequencies, the vibration gloves can even lead to an increase in vibration intensity (amplitude) instead of dampening. Because these gloves have such a poor performance they can lead to a false sense of security, resulting in the worker not employing any further safety measures to limit vibration exposure [36]. Some of these were originally just work gloves with a thickened layer, that were later rebranded as “anti-vibration gloves” [37].

pro’s	con’s
• Easy to use for the worker. • Cheap.	• Minimal effect, with some cases of increasing vibrations.

3.10.3 Vibration monitor

Devices that monitor the vibration exposure, such as the one shown in figure 30 [38], are available on the market. These devices help track exposure time according to a point counting system. Although they obviously do not do anything to diminish the vibrations, they do help form strategies to reduce exposure. In many cases these devices are not really fitted with vibration measuring sensors, but instead keep track of the duration of vibrations while the user has to manually input the declared vibration emission of the tool used.

Figuur 30: : A vibration monitoring device, worn around the wrist.

pro’s	con’s
• Easy to use. • Gives valuable insight.	Does not decrease vibrations.

3.10.4 Balancer

The Rocbo Absorption Balancer, as seen in figure 30 [39], offers a counterweight to the used power tool, so that the worker does not have to support the tools weight. This way the user does not have to exert their muscles as much as normal and makes it more feasible to work on high surfaces above the user’s shoulders. Vibration exposure is reduced by the frame absorbing part of the vibration, and by reducing strain on the user’s muscles. As discussed in paragraph 3.7.1 and 3.8.2, this would effectively reduce tissue damage from vibrations.

Figure 1: Rocbo Absorption Balancer

The worker does still hold the power tool conventionally, thus some vibration is unavoidably transferred into the hands and arms. In addition, the user still needs to manually put pressure on the tool for drilling or chiseling.

pro’s	con’s
Limits impact of vibrations.	Limits flexibility of use.

3.10.5 Trolley

The Makinex Jackhammer Trolley, as seen in figure 31. supports the weight of the jackhammer and separates the worker from the power tool, although the vibrations can still be transferred through the trolley frame.

pro's	con's
Effective against vibrations.	Very limited in application and use.

Figure 2: The jackhammer trolley in use.

3.10.6 Semi-exoskeleton (future)

The Lockheed Martin Fortis Exoskeleton, as seen in figure 32, supports a portion of the weight of the power tool, and by that will absorb a part of the vibrations [40].

pro's	con's
Reasonably flexible.	Expensive. Somewhat complex.

Figure 3: The Fortis Exoskeleton

3.10.7 Full exoskeleton (future)

The Sarcos powered exoskeleton, as seen in figure 33, supports all weight of any to be used power tool and can therefore absorb most, if not all of the vibrations [41].

pro's	con's
• Little vibration exposure.	• Limits flexibility of use. • Very expensive

Figure 4: The Sarcos exoskeleton.

3.10.8 Remote control robot (future)

The Hilti Jaibot, as seen in figure 34, is a semi-autonomous robot controlled from a distance. The operator is not in contact with the power tool and is there not exposed to any vibrations. [22]

pro's	con's
• No vibration exposure. • High precision.	• Presumably very expensive. • Limits flexibility of use.

Figure 5: the Hilti Jaibot in demonstration.

3.10.9 Conclusions

From this chapter can be concluded that no protection method or device reduces vibration exposure to any significant degree, or otherwise is limited in flexibility of use or very expensive.

- Anti-vibration technology is an improvement but does not change anything fundamentally. (*recommendations*);
- Anti-vibration gloves are only marginally effective. (*recommendations*);
- Anti-vibration gloves in some cases amplify the vibrations. (*recommendations*);
- No significant means of protection is currently available. (*recommendations*).

3.11 Existing solution analysis

The flexibility of use is important, as well as effectiveness against vibrations. From the previous chapter we can deduct that either a solution is very specialized , very complex, or not very effective. This is further illustrated in figure 35, where . Figure shows how the same protection devices compare in terms of ease of implementation. The comparison between products conveyed in these two diagrams are subjective, but serve as an exploration on how they likely compare to each other.
Many of the more effective measures from Figure appear to be more specialized to a particular job or tool, hence they are applicable to only a narrow range of activities, as seen in Figure 36. The gloves on the far left of the spectrum can be used for almost any tool and situation, while the Jaibot on the right, is only applicable in a select number of situations (e.g. when there is enough room and drill locations can be programmed).

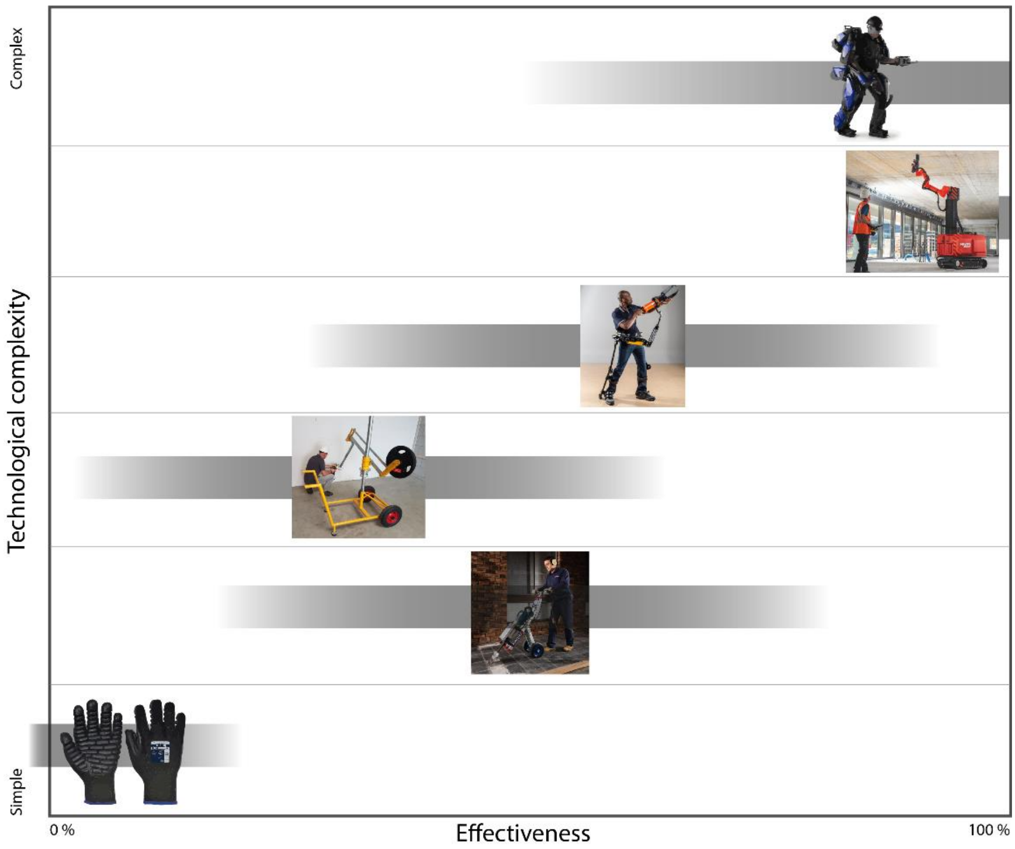


Figure 35: A matrix representation of the estimated complexity versus the expected effectiveness of the individual protection equipment.

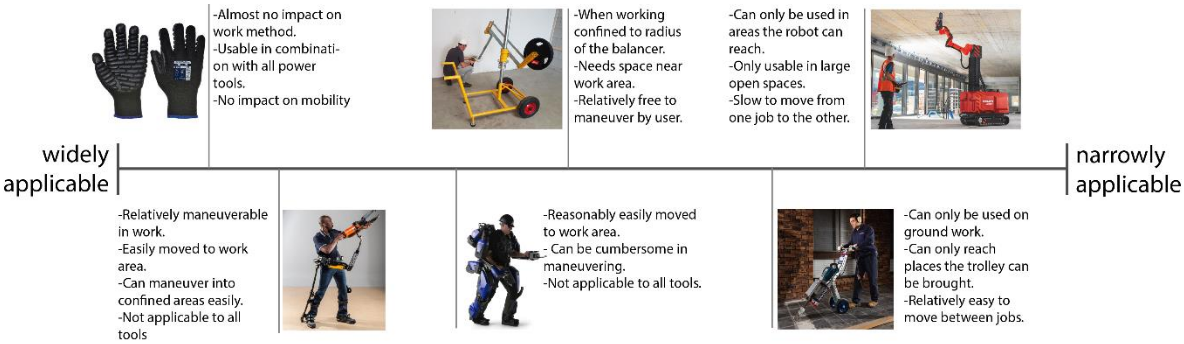


Figure 36: Protection devices compared on their range of applicability.

3.11.1 Conclusion

When comparing these values; apparent effectiveness, complexity, and range of applicability, it becomes clear that for most vibration exposure situations, there is no fitting solution available. On one side there are the anti-vibration gloves. These gloves are cheap and easy to use for almost any activity, however hardly effective against vibrations.

In between there are the balancer and the trolley. These two are reasonably effective against vibrations, and also significantly reduce the physical exertion of the worker. However, these are only usable in a limited number of applications. Especially the trolley, which only seems to be usable for demolition work along the ground surface, such as removing tiles. The balancer is more versatile than the trolley, but still limits the mobility of the user.

On the other side of the spectrum there are the exoskeletons and robots, which fall on the high end of the effectiveness spectrum. The semi-exoskeleton can be about as effective as the balancer, where the robot is presumably 100% effective against vibration exposure. In most cases these would be overkill: far too complex and expensive.

3.12 Program of requirements

Using the findings described in the analysis described up to this point, a list of requirements can be determined that the intended design should meet.

Req. no.	Requirement description	Paragraph	
1	**Performance**		
1.1	Design should increase worktime by 50%.	3.5	Workers may be exposed to a maximum of 2,5m/s^2 per 8 hours of work.
1.2	Design should not increase vibration by resonance.	3.10.2	With regard to low frequencies, anti-vibration gloves can amplify the vibrations.
1.3	The product must at least effective against the lower frequencies of <50Hz.	3.6.2	Percussive power tools emit frequencies mainly below 50Hz. (PVE/recommendations)
		3.5.4	According to ISO 10819 any vibration glove must at most transmit 90% of the frequencies between 25 and 200 Hz, and no more than 60% between 200 and 1250 Hz.
		3.5.4	Any personal protection equipment directed at vibrations must in particular address the vibration component harmful to the exposed body parts.
1.6	At least applicable to the power drill configuration, and other tools that have a pistol grip.		The hammer drill can be taken as a design focus, as it is comparable to a large variety of tools. (PVE)
2	**Flexibility and ease of use**		
2.1	Should not significantly impede freedom to maneuver when holding a power tool.	3.3	Protection gear that poses an impediment to productivity tends to be left aside.
2.2	The product must fit/be adaptable to different power tools.	3.6.1	A very diverse range of power tools is used in the construction industry.
		3.6.3	The hammer drill can be taken as a design focus, as it is comparable to a large variety of tools.
2.3	Should be intuitive enough in use, so that any worker can learn to use it in a single session.		
3	**Reduction of muscle exertion**		
3.1	(Wish) Should reduce muscle exertion of the hand and arm.	3.7.1	Operating a hammer drill itself requires exertion in the whole arm as well as significant clenching of the hand.
		3.7.2	Flexing muscles in the hand-arm system causes vibrations to propagate further up the arm.
		3.7.3	The subfunctions of holding (making connection) and holding the tool upright are important to distinguish.
3.2	(Wish) Should not weigh as much as to become a source of significant exertion itself.		
4	**Data collection**		

4.1	Should monitor and communicate vibration duration and severity.	3.3	Workers can be reluctant to report their injuries.
4.2	Data must be independent of declared vibration emissions (real time monitoring).	3.3	Construction companies and workers address safety issues in a reactive rather than pre-emptive manner.
4.3	(Wish) Should provide oversight on a management level by providing data on vibration exposure.	3.5.2	It is difficult for an inspector to determine for what duration a worker has been working with a given tool.
		3.5.2	The SZW Inspectorate would be greatly benefitted from data collection on hand-arm vibrations exposure.
4.5	Should give real time vibration data based on sensor input.	3.6.1	Within a single type of tool there is much variation in vibration emissions, depending on situation dependent factors.
4.6	Vibrations should be measured directly on the tool's handle.		ISO 20643
5	**Work environment**		
5.1	Should not stop working when any moving parts are contaminated with dust or sand particles.		
5.2	Should be resistant to abrasive effects of dust and sand.		
5.3	Should be resistant against extended periods of exposure to heavy vibrations.		
6	**Safety**		
6.1	Should not introduce new safety hazards to the worker.		
6.2	Should not be able to become a safety hazard by contamination of dust or sand.		
6.3	(Wish) Should have as little protrusions as possible that could possibly snag or hook on clothing or objects.		
7	**Product lifespan**		
7.1	The product should, under heavy use, at least last for 200 workdays.		
7.2	The parts that are essential to the user's safety and protection against vibration should be replaceable.		

3.12.1 Design vision

When taking the conclusions from chapter 3.10 and 3.11 into consideration, it becomes clear that no viable safety measures are available to effectively protect against hand-arm vibrations. Either a solution is ineffective (e.g. anti-vibration gloves and AVT), or it is only useful in a narrow selection of situations (e.g. the Jackhammer trolley and the balancer). For most work situations involving power tools, there is simply no safe way of performing the job for a reasonable length of time.

Therefore, an effective protection device is needed that both reduces vibration exposure to the worker, and is applicable in a wider variety of situations. The most important requirements, requirements 1.1 and 1.6, are formulated to this effect.
As stated in requirement 1.1, a protection device does not need to mitigate 100% of vibrations to be successful. Rather, it must at least make a significant difference in how long power tools can be used safely. That, in combination with a wide applicability of the protection device, so that many unsafe work situations involving power tools can be performed more safely.
Providing information on the vibration exposure in real-time can help the worker plan his activities and track any vibration exposure, while on a management level this data will help as well for prevention and work efficiency.
To meet these requirements this design process will be focused on testing and proving the underlying vibration mitigating technology, and designing a feasible and easy to use protection device.

3.12.2 Requirements with regard to entrepreneurship

The intention of using the product to found a startup brings allows its own set of requirements. Several of the previously mentioned requirements also offer benefits in entrepreneurial context. These are listed below, with the corresponding beneficial effect.

1.6	At least applicable to the power drill configuration, and other tools that have a pistol grip.	Applicability to a very common geometry ensures a large market for the product.
2.2	The product must fit/be adaptable to different power tools.	This widens the market the product applies to.
2.3	Should be intuitive enough in use, so that any worker can learn to use it in a single session.	This makes the product easily to adopt for users and their employers.
4.3	(Wish) Should provide oversight on a management level by providing data on vibration exposure.	This makes the product more attractive to the management level of a company, where the decision of buying the product is likely made.

In addition, there is the value of simplicity. Developing a product as part of a startup is made easier when the product is in principle less complex.

There is simplicity in terms of parts; A product that is small rather than large, with a small amount of parts, offers an easier iteration process. This means more iterations can be done faster, for less cost.

Then there is the simplicity in terms of underlying technology; A simpler technology is easier to understand, and work with. Often this also means less reliance on expensive electronics to prototype with. This too is beneficial to a startup as it makes the iteration process easier and cheaper.

4.1 Research & Design

4.1.1 Ideation

Protecting against vibrations through the use of a barrier is possible in many different forms and can be implemented in a protection device quite easily without changing its overall topology. Next to adding a barrier, there are many possible concepts that use an indirect (secondary) approach, such as reducing the vulnerability of the user, or by adding a support point where the vibrations can be absorbed into instead of the users hands (see chapter 3.10).

These indirect approaches (i.e. secondary to using a barrier) affect the overall topology of the protection device much more. To explore the possibility of using a secondary vibration mitigation solution, concept sketches have been made, as seen in appendix 6 . These explorations resulted in four basic directions which could be considered (also seen in figure 37):

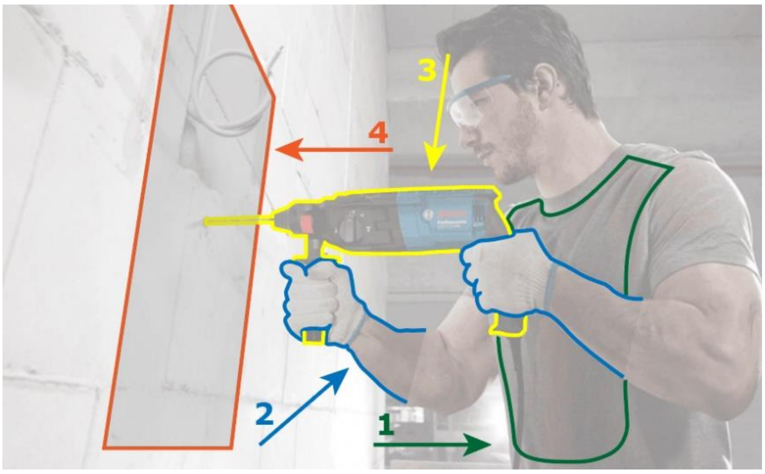
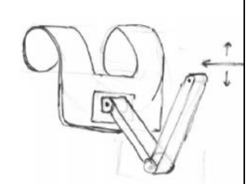
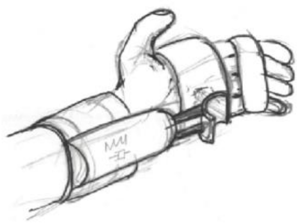
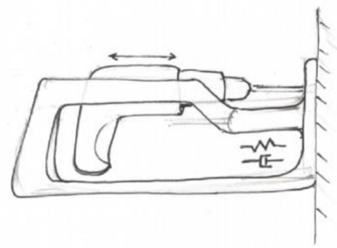
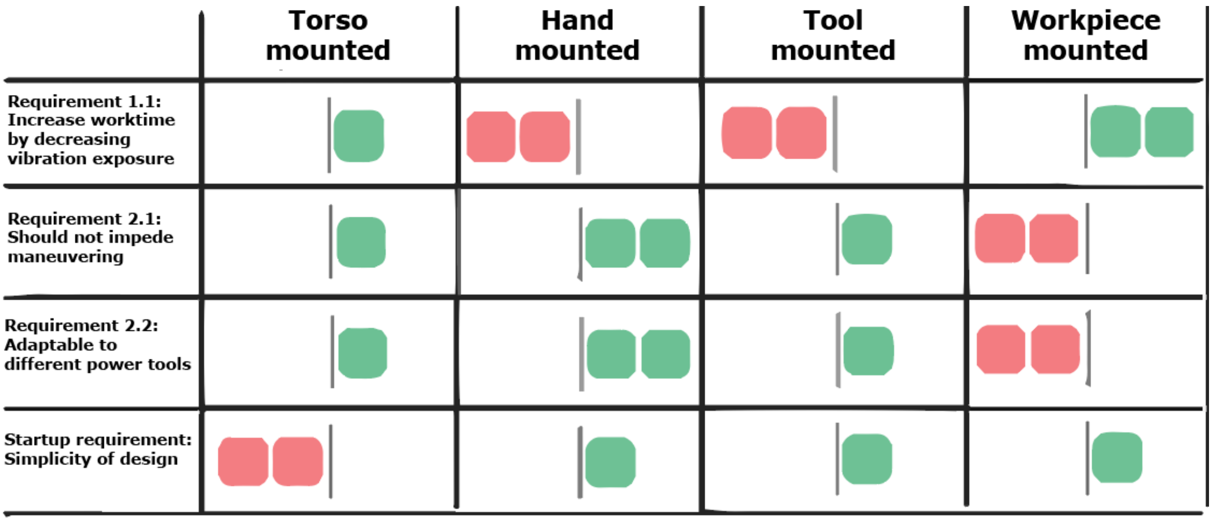


Figure 37: 4 Basic points of improvement towards mitigating vibrations.

1. Introducing a second support point, on the body. This redirects at least a part of the vibrations to the body, as well as part of the weight.
2. Adding a barrier to the hand or wrist, and thereby changing the way the hand couples with the tool.
3. Adding a barrier to the tool, and changing the way the tool offers a grip to the hand.
4. Introducing a second support point, on the workpiece. This redirects at least a part of the vibrations through the workpiece, as well as a part of the weight. The ground can also be considered as possible support point, but is left out since it is not applicable for many tool types.

1: Torso-mounted	2: Hand mounted	3: Tool mounted	4: Workpiece mounted
			

To adequately compare the solution directions mentioned above, a Harris-profile is used. The directions are compared according to the most important requirements as determined in the Program of Requirements (chapter 3.12). These are requirements 1.1, 2.1 and 2.2. Because these concepts are considered regardless of vibration mitigating technology, requirement 1.1 here refers to the ability of redirecting vibration into another object (e.g. the torso or the workpiece). Simplicity of design is added as a point of comparison to keep the goal of a startup in mind.



4.1.2 Conclusion

When interpreting the Harris profile it can be concluded that concept 2 (hand mounted) is the most promising direction. This concept fulfils requirements 2.1 and 2.2 and could be simple in design. direction 1 (torso mounted) is very complex in design and would require additional research to see whether vibrations to the rest of the body are harmless or not. Concept 3 (tool mounted) is too dependent on shape and topology of the power tool which makes it less broadly applicable. Concept 4 is too dependent on the nature of the work piece (i.e. work surface), which makes this concept less adaptable to different situations.

4.2 Metamaterial research

4.2.1 Choice technology:

With regard to the envisioned start-up, it is important to keep the final design close to what can be realised in a limited amount of time, and limited resources. The design direction is adjusted to achieve what is called a 'Minimal Viable Product' or MVP. This means that the product performs the core functionality adequately enough to be interesting for the customer, with minimal development time and costs.

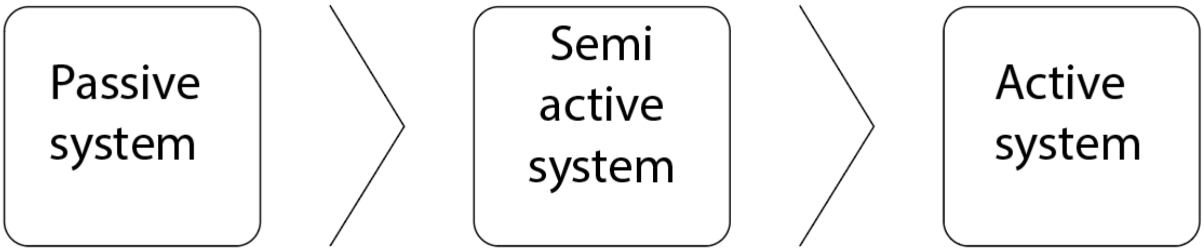


Figure 386: The order in which the basic vibration mitigating technologies should be pursued, with regard to a MVP.

Figure 37 shows the basic vibration mitigation technologies discussed in paragraph 3.9.2. With the definition of a MVP in mind, the first version of the product will incorporate a passive system in the form of a elastomer barrier. Since the vibrations emitted by a power tool have components in all 3 directions (x, y and z), therefore the choice of an elastomer barrier is preferable when compared to a mechanical spring or damper. An elastomer can absorb vibrations in all directions, no matter the geometrical design, in contrast to a mechanical spring or damper, which can only mitigate vibrations in one direction.

4.2.1.1 How to implement

Choosing an elastomer barrier still leaves many possibilities to choose from, in terms of material and geometry. The goal is to have a vibration isolator that is:

- Easy to determine and adjust the damping properties of
- Of an accessible technology, both in availability and complexity
- Easy to iterate upon

4.2.1.2 Inspiration

To explore possible technologies that fit the requirements stated above, inspiration can be drawn from products where this technology is already used. In this case running shoes are a good example, in which the soles are shaped in lattice structures to promote shock absorption while running.
For the development of these soles several studies have been performed to explore the properties and behaviour of several lattice structure designs. Based on these studies we now know that a grid shape tends to be stiffer, whereas a diamond shape is able to bend more (figure 39) [42]. These variations in shape, along with material thickness, provide the possibility to adjust and tailor for specific applications, also outside of the running shoe context such as the development of a suitable vibration damper Figure 40 & 41 [43]. The envisioned application in damping vibrations form power tools is still novel, but this method offers a good starting point to develop a suitable vibration isolator .

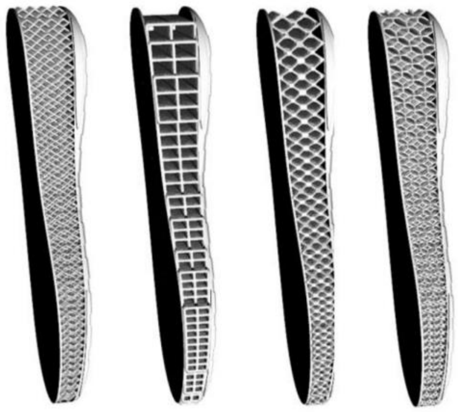


Figure 39: Lattice structures researched for shoe soles.

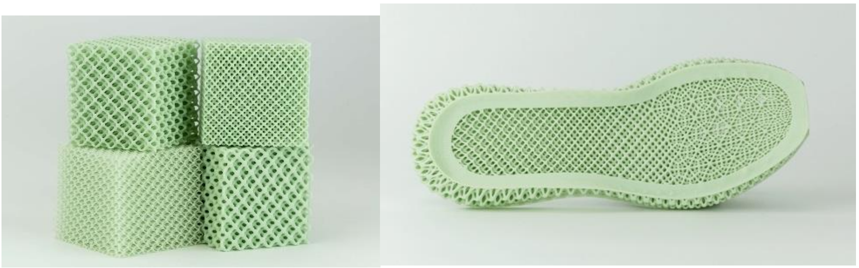


Figure 40 and 41: Lattice structures used in a shoe sole concept.

4.3 Damping material exploration:

4.3.1 Why an experiment

As previously mentioned, absorbing shocks using an elastomer lattice structure is an established technique in the running world, but not enough existing literature is available to support a meaningful design in vibration mitigation context. To be able to develop a successful elastomer damper a new experiment should be conducted aimed at exploring elastomer behaviour in a vibration context. By basing the design of the damper on a material experiment the final choice of elastomer design will more credible and scientifically substantiated. These considerations are especially important with regard to the goal of developing a product suitable for a start-up company.

Taken together this experiment is necessary for the following reasons:

- Proving this technology is a viable and practical method of damping vibrations emitted by power tools.
- Providing credibility to the following product design.
- Exploring the potential difficulties that this technology could pose.
- Becoming more familiar with the used material.

4.3.2 Test design

To be able to objectively test different elastomer designs, a test setup will be developed. Based on the running shoe studies several elastomer test objects will be designed and tested for vibration isolating properties. The same set-up as analysed in chapter 3.7 is taken as a starting point. To have a valid test set-up several requirements should be met to accurately represent the equivalent of a real-life situation:

The experiment must accurately represent the equivalent real life situation as much as possible in five key aspects:

1. A vibration profile similar to that of the proposed power drill.
2. Represent variation in the pressure force, similar to when a worker handles a power tool.
3. The experiment must be repeatable for multiple test objects.
4. The experiment must provide simple, manageable data that can be analysed and compared.
5. The set-up must be easy to build in a limited time, with limited resources.

4.3.3 Test setup

The final test setup is comprised of a wooden frame supporting all the needed components including a hammer drill. Using a hammer drill instead of an artificial vibration source guaranties the vibration profile used for the test is representable for a real-life situation. The drill was suspended by two linear rails (A), making the drill able to move in only one direction along the centreline (forward-backward). When pushing the drill forward along the rails the tester was able to drive the drill into a wooden plate mounted on the wall (B). By focusing on one movement direction the data analysis was simplified.

The test object (C) fits into the back of a mounting piece which is fitted to the tools handle (D). When testing a test object, an IMU sensor is placed in the hand rest (E). The vibrations will travel through the handle, mounting piece, and test object before being registered by the IMU sensor. For the baseline test, the IMU sensor is located in the mounting piece (D), and the hand was placed directly onto it. For simplicity, the experiment was limited to the vibration emission as measured from the handle of the power tool.

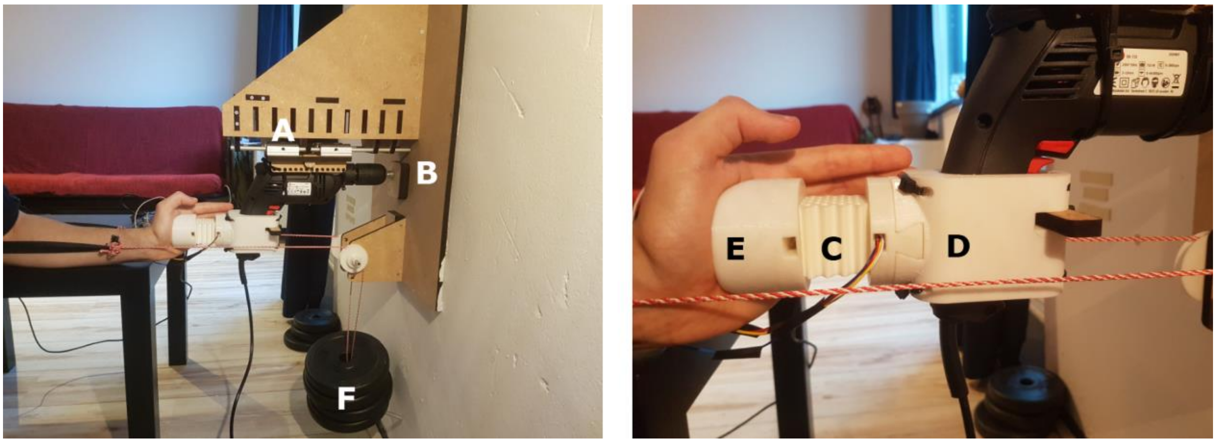


Figure 42: The test setup, With the individual parts indicated in A-F.

To simulate a worker putting pressure on the power tool the arm is drawn towards the wall using weights (F) via pully system. This drives the whole arm-damper-tool system into the wall with a standardized weight and direction. This way, for each test object the setup is exactly the same each time, making the test results comparable. The experiment was performed with three different pressures exerted onto the power tool, i.e. 30, 50 and 70N.- The arm was relaxed as much as possible during the measurements, as additional tension in the arm can influence the vibrations registered.

4.3.4 Data analysis

The raw acceleration signal already gives an at face quantification of the dampers used. Simply comparing the vibration profiles of one measurement with the other can show which damper is more effective (less amplitude is more damping). To gain a more in depth understanding of the vibrations measured the frequencies present in the signal can be quantified by a power spectral density plot (PSD), acquired through a Fast Fourier Transformation of the accelerometer data. This plot shows the dominant frequencies present in the vibration profile. A limitation of the sensors used is the limited sampling frequency of 100Hz (100 measurements per second). As a consequence, to avoid aliasing of data only frequencies of 50Hz and lower can be meaningfully interpreted. However, in the context of this experiment we know based on literature that the lower vibrations are more important, as most of the vibration emitted by a power tool are of frequencies below 50 Hz.

4.3.5 3D printed vibration absorbers

As discussed in chapter 3.9, low frequencies require the corresponding damper to have low stiffness, This is also an important fact with regard to the main challenge of designing a vibration damper for power tools, as this low stiffness is a problematic combination with the fact that the user should excerpt force on the power tool through this vibration damper. In use the design would actually benefit from a damper with high stiffness as manoeuvring and controlling the power tool with a stiffer connection is more feasible. However, a connection with low stiffness mitigates vibrations better. This opposition will be a design challenge for both the development of a vibration isolator as well as incorporating this in an ergonomic prototype.

4.3.6 First experiment

The test objects of the first experiment were 3D printed with a shore 95A filament, except for object #8, which was printed with a shore 85D filament. Each object is a simple representation of a lattice structure design, varying in geometry and material thickness. This way different parameters could be explored for their vibration isolating properties. The test objects were designed to be interchangeable within the test setup, with identical outer dimensions. The decision tree illustrating the iteration process based on all included test objects and their corresponding results are presented in appendix 7.

4.3.6.1 Results

In figure 43 and 44 the results for the 5kg and 7kg tests are shown. The results show that none of the test object performed particularly well. None of the test objects diminished the vibration when compared to the baseline test in blue. The Power Spectral Density plot shows several substantial peaks of increased magnitude around 31 to 34 Hz compared to baseline.

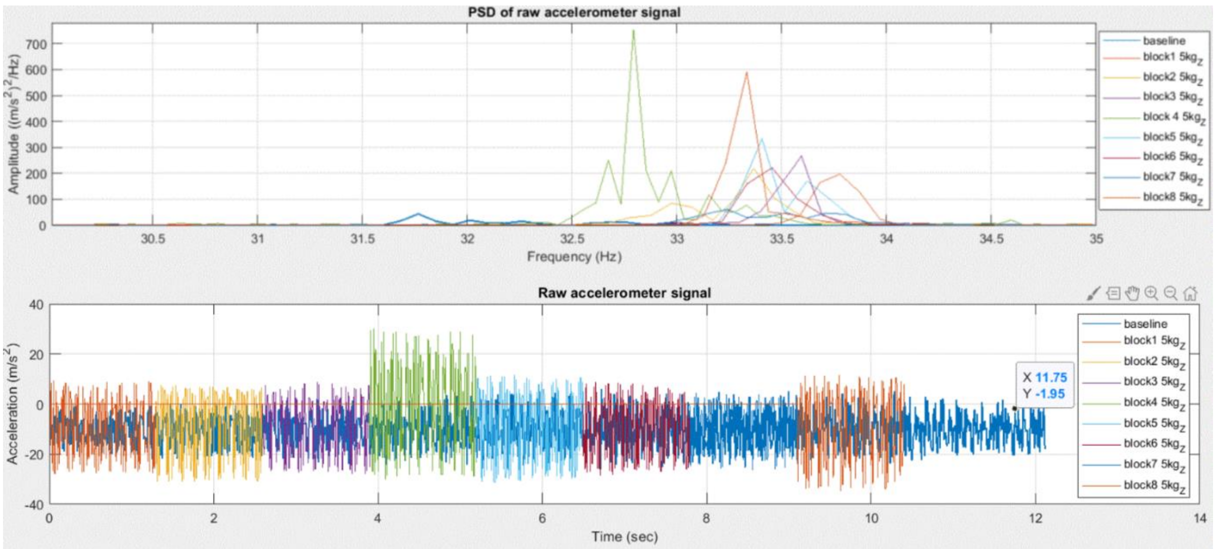


Figure 43: 5Kg tests. Top window: The PSD shows large increases in vibration magnitude between 30 and 34 Hz. Bottom window: The raw vibration data (acceleration). All vibrations have a larger amplitude than the baseline, which means that none of the test objects diminished vibrations, and some even largely amplified the vibrations.

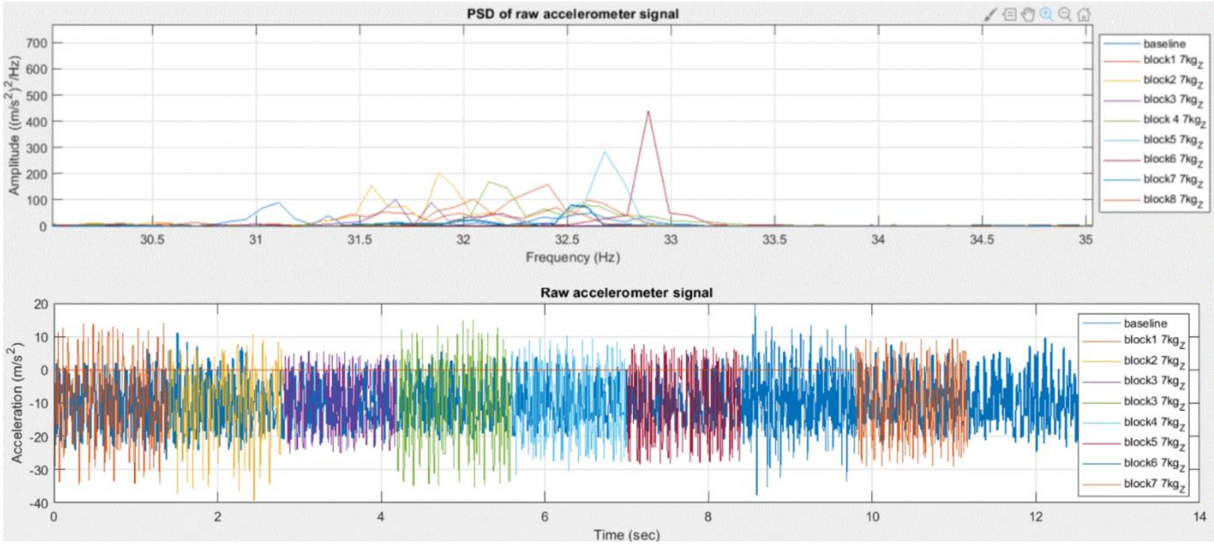


Figure 44: 7Kg test. Similar results as in the 5kg test. The raw vibration data shows that in this test the test objects do not amplify vibration as much as in the 5kg test, but they still do not diminish the vibrations compared to the baseline.

4.3.6.2 Conclusion

From the results it can be concluded that 3D printed is not suitable for mitigating vibrations. None of the objects reduce the emitted vibrations in any meaningful way, and some test objects even increase vibrations.

4.3.7 Second Experiment

Based on the results of the first experiment it could be suggested that a softer material might offer better results. New test objects with similar dimensions as in experiment one where made using silicon with shore 25 (object 9 and 11) and shore 45 hardness (object 10 and 12). The decision tree illustrating this iteration process based on all included test objects and their corresponding results are presented in appendix 8.

4.3.7.1 Results

The result are again shown in PSD and raw acceleration data, for the 5kg test in Figure 45, and the 7kg test in Figure 46. In both tests the silicon test objects perform better than the 3D-printed objects in the previous experiment.

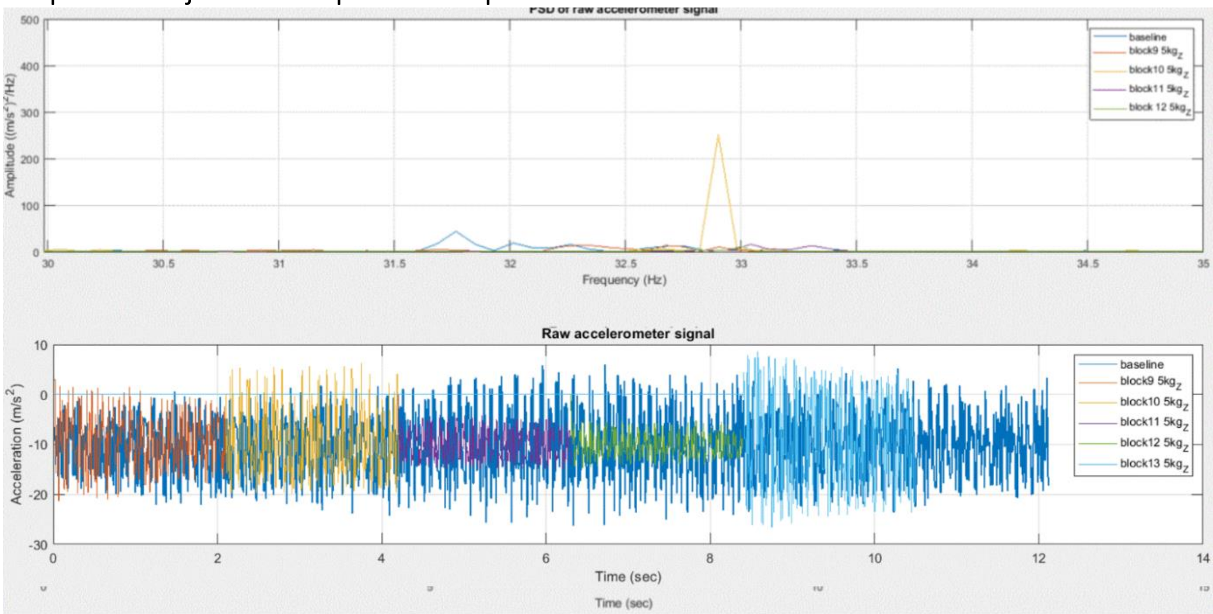


Figure 45: 5Kg test. Only object 10 amplifies vibrations. All other objects showed lower vibration magnitude than baseline. Block 12 showed the best result, followed by block 9.

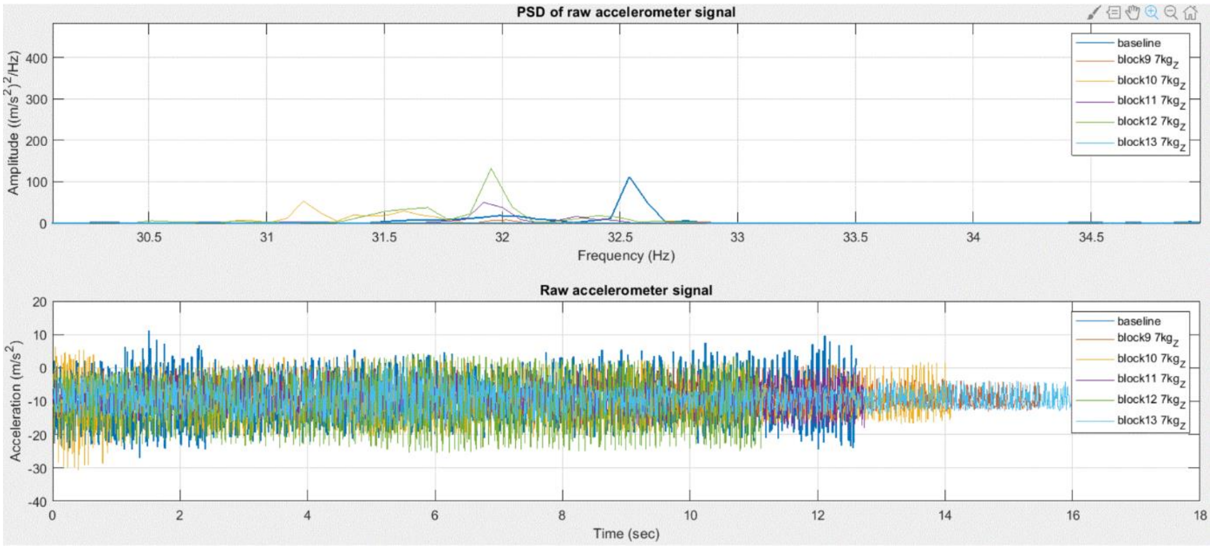


Figure 46: 7Kg test. Block 9 performed best in this test, followed by block 10 as can be seen as the obviously lowered amplitude of the vibrations compared to baseline.

4.3.7.2 Conclusions

The silicon test objects in this experiment overall performed better than the 3D printed objects of the first experiment. Especially object 12 performed well under both weights (i.e. 5kg and 7kg). Object 13 performed well under 7 kg. During the experiments it was noticed that the 5kg testing seemed too light to represent an actual real life situation, and that the 7 kg test was probably a better representation. for this reason both object 12 and 13 will be used in future testing.

Both object 12 and 13 showed an amplitude of around 5 m/s^2 in the 7kg test, compared to a 10 m/s^2 amplitude for the baseline. This constitutes a significant improvement, which means that this method of vibration mitigation can be considered a viable method to design a protection device with.

4.4 Design by prototyping

The research conducted up to this point firmly established the need for a protection device that makes it possible to do a job adequately and unhindered, while offering enough protection to substantially increase the time of working within regulatory limits.

For this purpose, special consideration is given to the earlier mentioned requirements of wide application across different tools and activities, and being easy to use and manoeuvre during a variety of working activities.

4.4.1 Further exploration of hand-held concepts

At this point in the design process, ‘hand-held’ is still a very broad concept. It is clear that the protection device will be centred around the hand, but this leaves many possibilities that need further exploration for feasibility.
To this end, a new brainstorm session of sketching was done to explore this design space. Some inspiration was drawn from existing products, such as gloves and wrist protection (Figure 47).
These sketches are available in appendix 9. This approach of exploratory sketching was aimed at providing some orientation towards the process of prototyping. What aspects of the design are important to explore, and what are likely options to draw from. To start, three general prototyping directions were identified this way: Full hand glove, palm brace, and wrist brace.

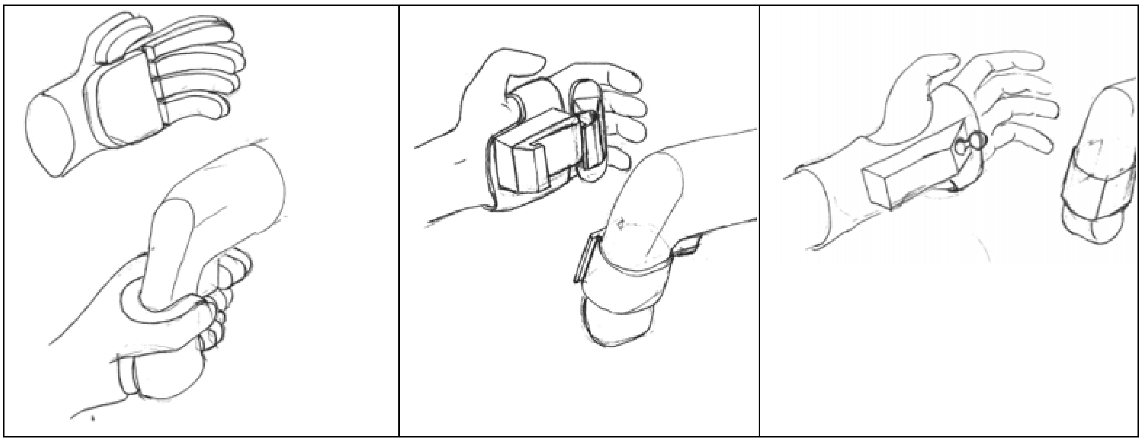


Figure 477: Sketches of the 3 prototyping directions: Full hand glove, palm brace, and wrist brace.

4.4.2 Full hand glove

Since the anti-vibration gloves currently on the market serve as a prominent design influence and as a benchmark to the design, it is natural to include a design that is close to the archetypical glove. The first prototype (figure 48) is made by fixing a thick layer of foam to the medial side of the glove, as a mock-up for the envisioned elastomer buffer. A split is made along the base of the fingers and thumb to allow bending. This thick layer impedes the ability of the wearer to close the hand completely during a grabbing action.

Figure 48A and B, First prototype. Thick padding covering the palm and fingers.

Learning from the first prototype, another prototype was made with additional splits along the natural hinging lines of the fingers and palm (Figure 49). The thumb is fitted with a separate piece of foam, more adjusted to the natural position while grabbing, since the thumb is an opposing digit relative to the other fingers. This prototype allows the hand to perform a grabbing action, although noticeably reduces grip strength. However, this prototype seems feasible to work with.

Figure 49A, B and C: Second prototype. Adjusted to the hand with splits to make grasping easier.

The third prototype was aimed at improving the reduction of grip strength (Figure 50). Instead of carving the shape out of a flat piece of foam, the shape was instead carved in the shape of a closed grabbing hand. Incisions were subsequently added to allow the glove to be opened. This way, less strength was needed to deform the foam itself when closing the hand. However, when grabbing and actually holding the drill the lack of grip strength remained similar to the second prototype, with no significant improvement.

Figure 50A, B and C: Third prototype. An iteration on the splits in the second prototype.

4.4.2.1 Conclusion

Handling these three prototypes gave the insight that the problem of grip strength is intrinsic to the concept of adding a significant buffer to the medial side of the glove. As this is the core element of this design direction it can be concluded that this design direction is will not lead to a useful design. This outcome was to be expected when considering that none of the available anti-vibration gloves on the market incorporated such thick buffers.

4.4.3 Wrist and palm mounted concepts

The wrist and palm concepts are somewhat similar in that they rely on introducing rigid elements to the device. This helps to transfer the vibrations through the damper, and provide a rigid connection with the power tool handle. When the hand performs the grabbing action as in the full hand direction, it naturally determines the rigidity and relative positioning of the connection, in relation to the handle. This results in the handle being always in the middle of the palm, and the force with which the hand clenches determines the rigidity of the connection. The other two concepts, mounted on the palm and on the wrist, replace the hands grabbing action and therefore the positioning of the hand and the rigidity of the connection can be determined freely and in several ways. To explore the options, several modular prototypes where developed. Additionally, a place holder design for the elastomer buffer was used (picture 53). To form an easy way to connect the prototype to the power tool a so-called sleeve was added to the handle of the power tool (picture 51). Both the buffer and the method of coupling to the power tool will be revisited later in the design process.

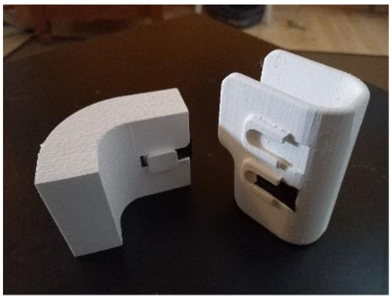


Figure 51: Slot and ledge connection in the buffer and handle sleeve.

Figure 52: The place holder buffer.

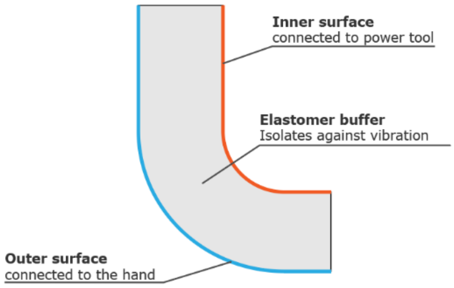


Figure 53. The buffer explained.

As seen in picture 53, the outside of the buffer formed a rigid frame connected to the hand. The inside of the buffer formed a rigid frame that connected to the handle of the drill. This way the only mechanical connection between the hand and the power tool was directed through the elastomer buffer in between.

4.4.3.1 Wrist mounting - positioning and angle

The rigid wrist brace was modelled on an existing wrist protection brace. The original plastic part was removed and replaced by a 3d printed model, which acted as a mounting surface for the place holder buffer. Of the rigid plate in the wrist brace an angled and a straight version were tested, corresponding to the two angles of connection on the place holder buffer (figure 54). This allowed for several combinations of positioning and angle of the hand in relation to the handle.

Figure 54. The straight and angled wrist mount.

The straight version placed the handle of the power tool right next to the hand (figure 55 and 56). It gave good sense of control over the power tool. Noticeable was that the narrow mounting plate caused the connection between the hand and power tool to be quite unstable. The power tool had a high placed centre of gravity relative to the position of the hand. When toppling over, the wrist mounting seemed unsuitable to transfer the counteracting force of the hand, making the connection unstable.

Figure 55A and B. A shows the drill being help on its side. This increases the moment exerted on the brace. 55B shows the direction of this force.

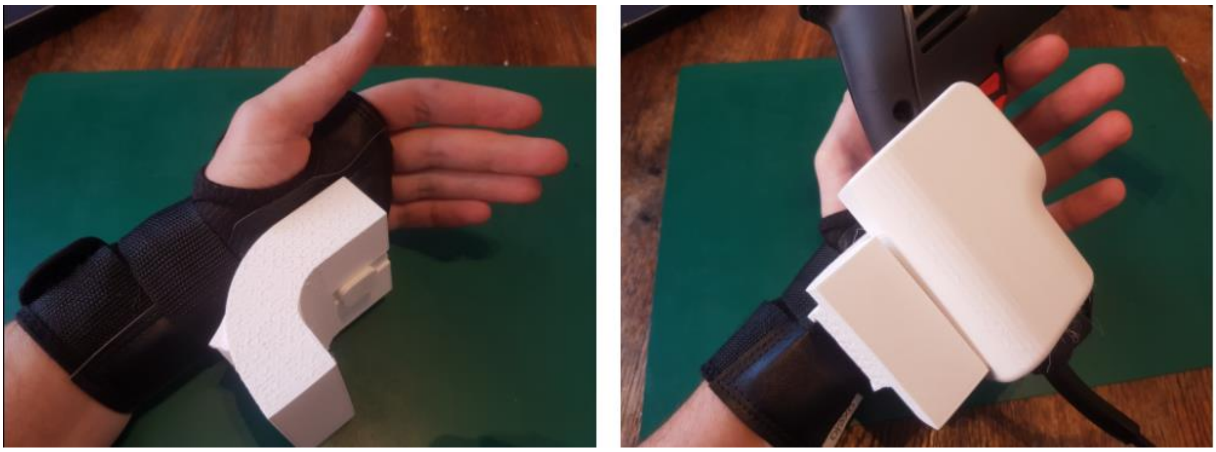


Figure 56A and B. A shows the straight wrist mount, with the buffer attached.56B: When holding the drill, the fingers can easily reach the controls.

Considering the angled mounting variation: this put the hand far from and behind the handle (figure 57). Although the angle of the hand felt natural, the hand was put far behind the centre of gravity of the drill, which increased the exertion needed to hold the drill upright (Figure 58).

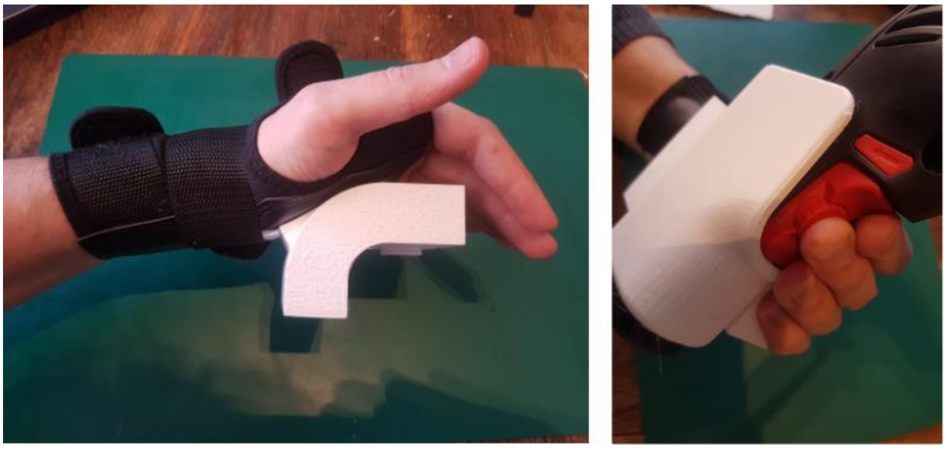


Figure 57A end B. A shows the angled wrist mount. 57B: the fingers can just about reach the controls.

Figure 58A and B. A shows the position of the hand in relation to the drill handle. In this position the drill tends to topple forward, 58B shows the direction more clearly.

Conclusion: The straight wrist mounting gave sufficient support in keeping the drill upright, where the angled version put the hand too far behind the handle. In both versions it was difficult to keep the drill upright in sideway position due to the increased moment.

4.4.3.2 Palm mounting - positioning and angle

The palm mounted brace was made in two variations: a rigid frame that enveloped the hand all round (Figure 59 A and B), and a version that just covered the palm and was fixed to the hand with straps (Figure 59C). The rigid version proved too constricting to the hand and in any case would be difficult to make properly fitting.

Figure 89A B and C. A shows the palm brace with the connection ledge. B shows the fully enveloping hand brace. C Shows the half palm brace strapped to the hand, with the buffer attached.

The palm mounting prototype, gave a good sense of control over the power tool. The brace had a much broader support on the palm, and by that did not have the problem of sideways stability as was noticed with the wrist mounting prototype (Figure 60A). The angled position did have the same problem as the angled wrist mount in that it placed the hand far from the handle (Figure 60B). In this case it was noticeable that the hand needed to be flexed in order to keep a stiff enough connection between hand and palm brace.

Figure 60A and B Show the palm brace holding the buffer in two positions.

4.4.3.2 Conclusion

The palm brace enabled much more control over the power tool in preventing the tool rolling over sideways. When in angled position it was difficult to keep the drill from toppling forward.

4.4.4 Wrist palm combination

A better result was reached when wearing the straight wrist mounting and the palm mounting on top of each other (figure 61). This indicated what is perhaps already quite evident, that a combination of both will perform much better.

Figure 61A, B and C. The wrist and palm prototypes worn on top oof each other.

Adding an extension and wrist support to the palm brace was a first attempt at an integrated version (Figure 62). From this prototype it could be concluded that the extension was too long. It noticeably made moving the hand and wrist more cumbersome. In addition, the wrist support was too small and tended to create pressure points on the skin.

Figure 62A, B and C. First combined prototype, with an extension to the wrist

The final version was much more comfortable and fitted the wrist and hand so well, that it stayed on without any other parts (Figure 63). The wrist support was wide and flexible, and enveloped the wrist in a U-shape. The connection between the palm brace and the wrist support was curved outwards to make sure it did not cause discomfort on the wrist when moving. The prototype could also flex slightly, which allowed slight movements of the wrist.

Figure 63 A, B and C. The second combined prototype fits much better on the wrist.

4.4.5 Buffer shape

Until now a place holder buffer (Figure 51-53) has been used to connect the hand mounting piece and the power tool. This shape can be redesigned to better integrate with the hand mounting and perform its damping function.

The buffer needs to:

- Have as much depth in each direction of the handle as possible for optimal grip.
- Allow the hand, and especially the thumb, to wrap around the handle as naturally and closely as possible.
- Have enough volume to absorb the vibrations from the power tool (to be investigated later).
- The first version of an integrated buffer fused the palm mounting and the buffer by getting rid of the sliding connection that was part of the previous prototypes (Figure 64). The inside surface of the buffer was shaped to fit the handle more closely. Noticeable was that the buffer shape blocks the thumb from making any kind of grabbing motion.

Figure 64A, B and C. A Shows the original place holder buffer, compared with the first buffer prototype shown in B and C.

A second version was aimed to solve this problem (figure 65). A part of the hind portion of the buffer was removed to make room for the thumb. The down side of this version was that it left little volume for a buffer to absorb vibrations.

Figure 695A, B and C. The second buffer prototype, with more room for the thumb to move.

The third version had an increased volume of buffer behind the handle by expanding the shape towards the wrist, and upwards while leaving enough room for the thumb (Figure 66). Considering the previous prototypes, this version seemed to have a favourable compromise between volume and freedom of movement of the thumb.

Figure 66 A, B and C. The third buffer prototype, with an extended buffer volume towards the wrist.

4.4.6 Conclusions

This series of prototypes has yielded a hand and wrist mounted prototype that offers a stable connection between hand and tool, with special regard to the hand positioning in relation to the power tool handle (Figure 67). the buffer volume in design is maximized given the spatial limitations. Most volume is put behind the handle, and below the thumb. The stability of the hand-tool connection is achieved by a broad support across the width of the palm, with a short wrist support connected along the bottom of the frame.

This prototype will serve as a basis for further development.

Figure 67A, B and C. The final buffer prototype combined with the final combined prototype.

4.5 Prototype integration and testing

The prototype developed in paragraph 4.4 is for simplicity made as a solid 3D printed object. of course this is not adequately representative of an actual working version. The purpose of this paragraph is to combine the previous results into a working version and to test it for the relevant properties. This is done by merging the result from the vibration experiments described in 4.3.7.2, with the wearable prototype from paragraph 4.4.6.
As seen in figure 68, a new prototype is made to integrate the elastomer buffer developed in paragraph 4.3. The individual parts are connected with slots, so that the buffers can be exchanged for testing.

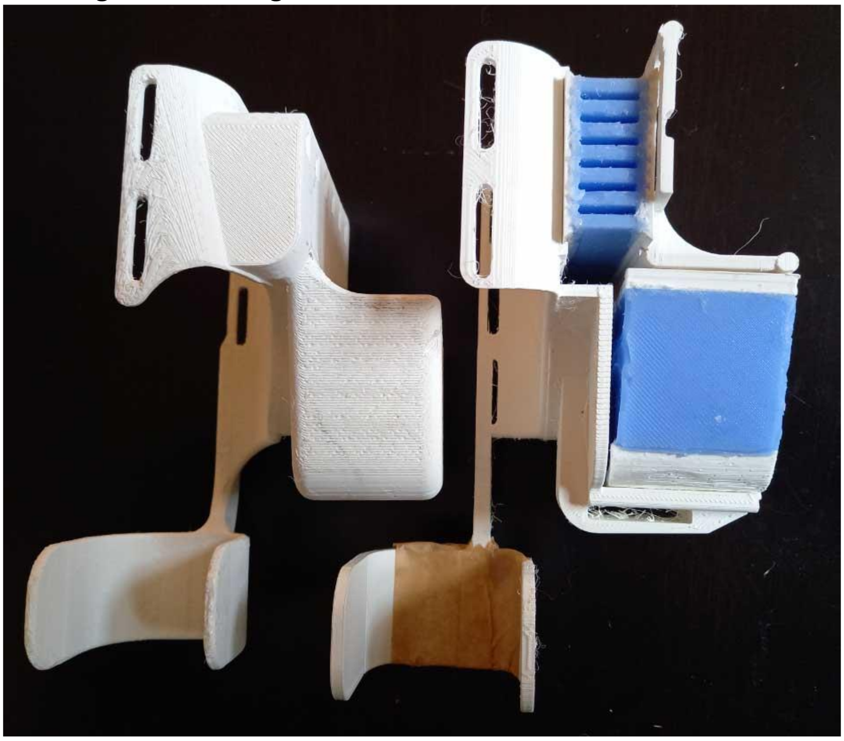


Figure 68: The prototype from paragraph 4.4, compared to the integrated prototype.

4.5.1 Buffer characteristics

Because all the mechanical interaction between the hand and power tool needs to go through the elastomer buffer, the buffer has an essential role in performing two important functions of the protection device; offering a stable connection to handle the power tool; and to isolate the hand from vibration emitted by the power tool. The combination of these two design values raises the question of how to design the buffer to meet both requirements.

To simplify answering this question, the buffer is split up into two parts: the rear buffer, and side buffer. These parts each have a separate function:

- The rear buffer absorbs the longitudinal force (Y-direction) from putting pressure on the tool while working, and absorbs the majority of the vibrations (Figure 69A).

- The side buffer is designed to interfere as little as possible with the longitudinal force and vibrations in the Y-direction. As seen in figure 69B, the side buffer deforms easily in the Y-direction. The side buffer offers more resistance in the X-direction, for stability.

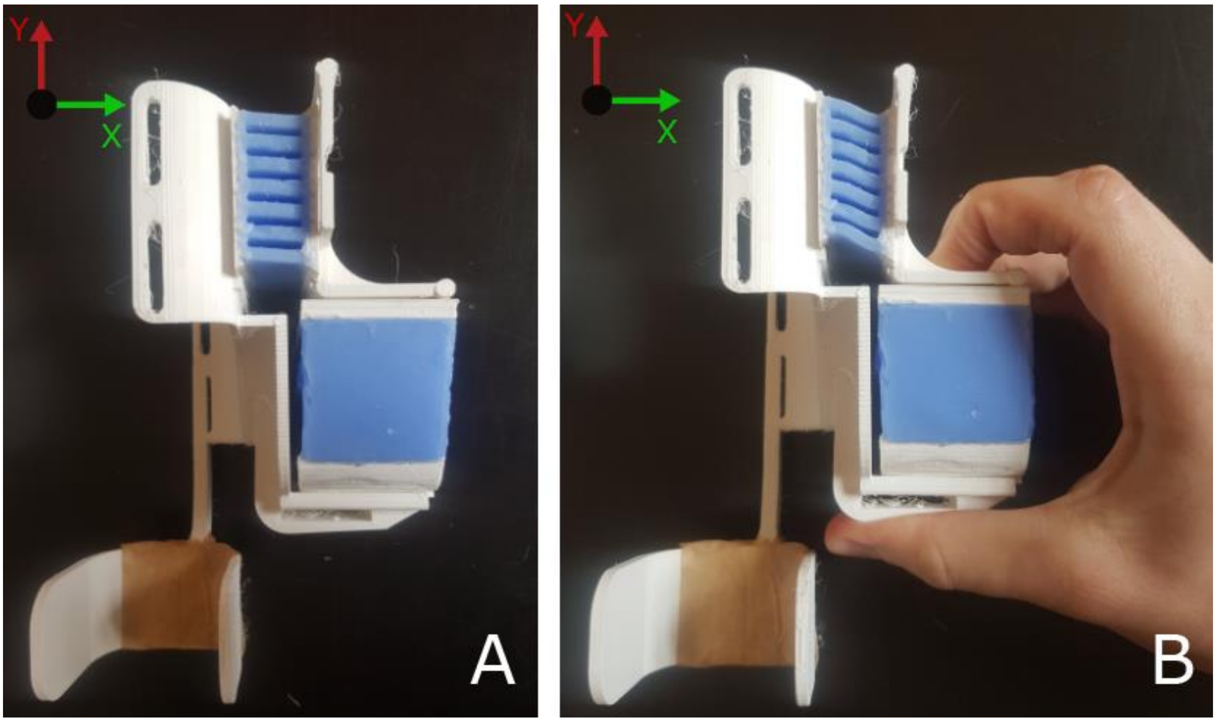


Figure 69A and B: The rear and side buffers deforming under pressure in the Y-direction.

The test objects in 4.3.6 and 4.3.7 have been tested in one direction only, while in real use the emitted vibrations are present in all three dimensions. For simplicity this prototype is also designed with regard to damping vibration in the Y-direction only. Vibrations in the X-direction in figure 69 are left out of the scope of this thesis.

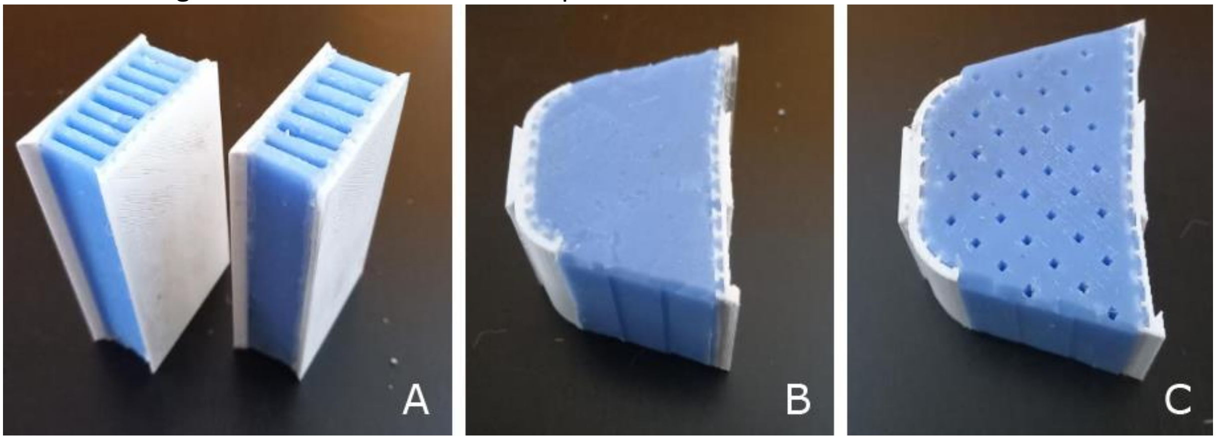


Figure 70: The elastomer buffers used in the integrated prototype. 70A shows the side buffer with two different geometries. Only the stiffest of the two is used in the experiments. 70B shows the solid rear buffer based on object 12 from paragraph 4.3, and 70C shows the grid rear buffer based on object 13.

This prototype is tested to answer the following questions:

- Does the prototype offer the intended stability?
- Does the integrated prototype still isolate the user from vibrations, and to what extend?
- Does handling a power tool using the prototype require less muscle contraction?

4.5.2 Prototype stability

The stability of the hand-tool connection is a function of the stiffness of the buffers, particularly that of the side buffer. In this paragraph this stability is tested.

In use it is more likely that the power tool is held using two hands, in which case there is not much of a stability problem with regard to the connection of a single hand and the handle (Figure 71). It is still useful to look at the situation of one hand holding the power tool using the protection device, simply as a measure of the stiffness of the connection. In addition, single handed use is still a possible way in which a user might want to use the protection device. That is why in this paragraph the stability will be tested according to single handed use.

Figure 71: The power tool held with two hands. In this situation

4.5.2.1 Toppling forward

The first stability test is done by holding out the power tool unsupported and letting it deform the silicon buffers by its weight. As seen in Figure 72A, the power tool topples forwards significantly. Figure 72B shows how this deforms the buffers, especially the side buffer.

Figure 72A and B. 72A shows that the power tool topples forward significantly. 72B shows in detail how the buffers deform.

4.5.2.2 Toppling sideways

The second stability test is done by holding the power tool on its side, as seen in figure 73. This also puts significant strain on the side buffer in particular. In this direction the power tool also

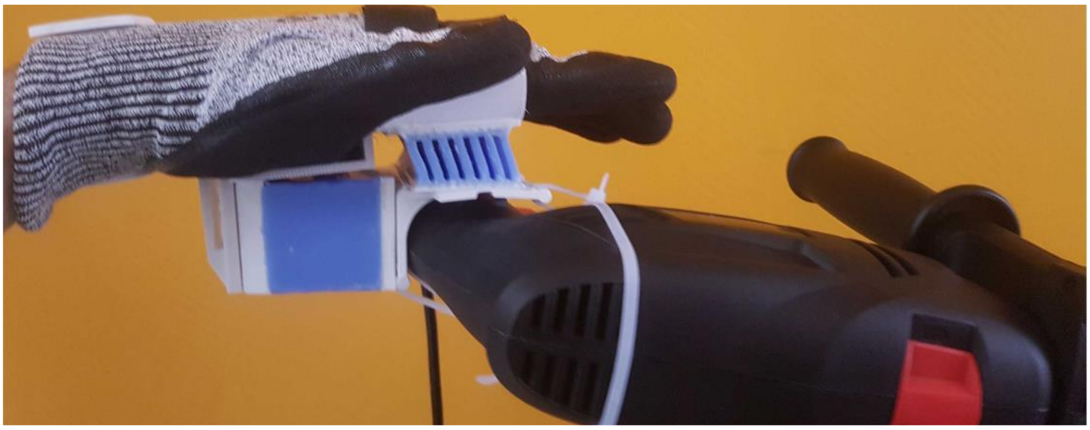


Figure 73: The power tool deforms the side buffer significantly when held on its side.

4.5.2.3 Conclusion

the silicon side buffer clearly deforms by the weight of the power tool in both situations. In order to improve this, especially the properties of the side buffer should be changed. This needs to be taken into consideration when further developing the elastomer buffers.

4.5.3 Vibration isolating performance

To validate the vibration isolating performance, two different dampers are placed in the protype for testing. The integrated prototype is tested in the same test setup as used in paragraph 4.3. The prototype can be directly connected to the power tool handle and worn as designed. The sensors are embedded on either side of the side buffer.

4.5.3.1 Test setup

The sensors are placed differently than in the experiment in paragraph 4.3 where the sensors where placed on either side of the test object. In this test however, the integrated prototype needs to be tested in its entirety. For this reason the sensors are placed to measure the cumulative vibration mitigating effects of the prototype. For the baseline the sensor is placed directly against the power tool handle (as seen in figure 74B and 75A)to measure the vibration emission of the power tool. To measuring the effect of the of the prototype the sensor is placed directly against the hand (Figure 74B and 75B).

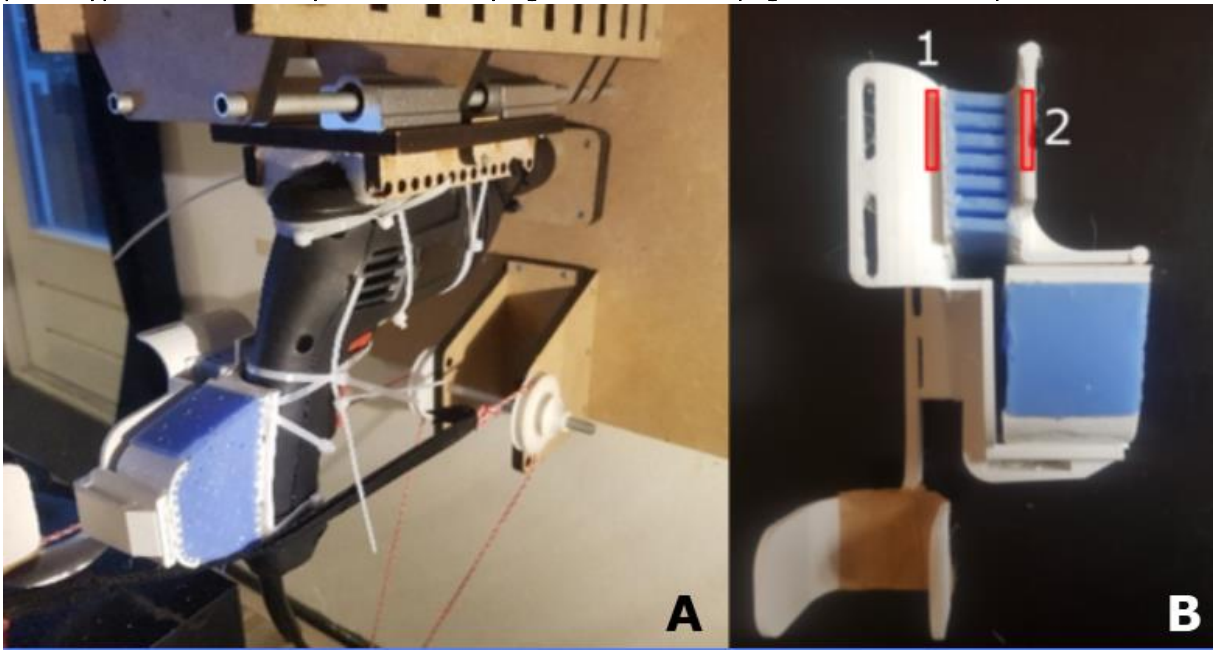


Figure 74A and B: 74A shows the test setup with the integrated prototype connected to the power tool. 74B shows the locations of the sensors. Sensor 1 is used to measure the cumulative effect of the prototype, and sensor 2 is used to measure the baseline vibration.

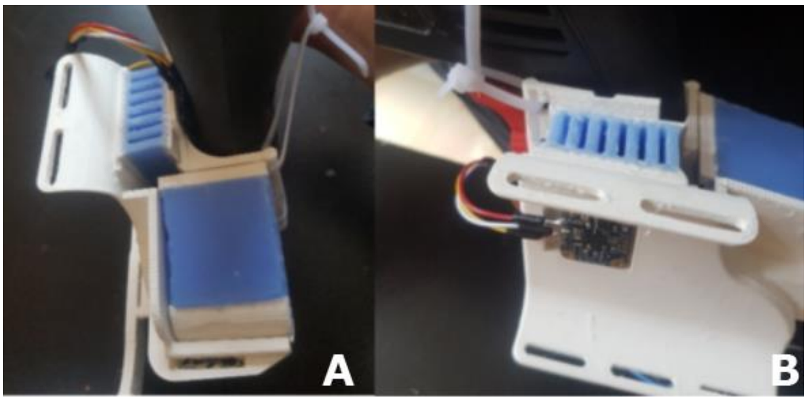


Figure 75A and B: 75 A shows the sensor embedded in the prototype directly in contact with the handle. 75B shows the sensor embedded in the prototype where the palm of the hand is placed.

4.5.3.2 Results

As seen in figure 76, the data from the vibration test shows that the solid rear buffer reduces vibration considerably, while the grid rear buffer achieves almost no reduction. The maximum amplitude of the solid buffer is approximately 5 m/s^2 compared to a maximum amplitude of approximately 15 m/s^2 for the baseline. In the PSD data the dominant frequencies of the baseline are clearly visible, where the solid buffer shows almost no dominant frequencies.

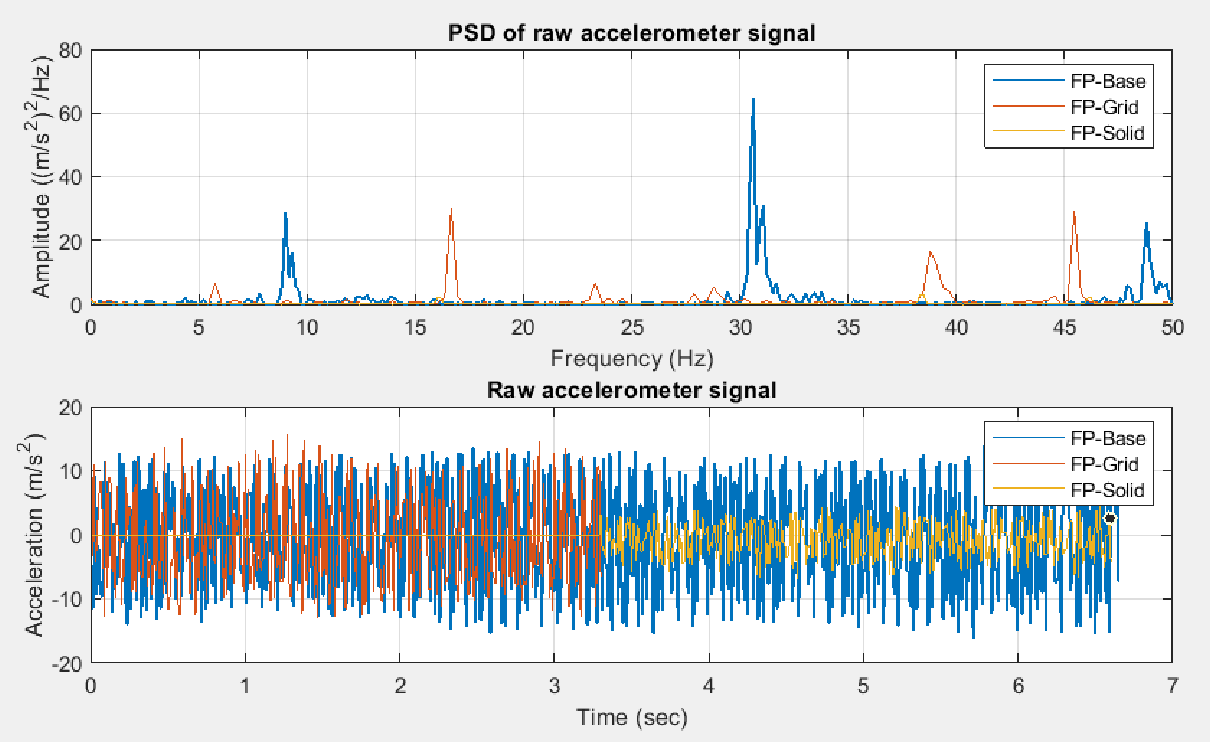


Figure 76: The data results from the vibration tests, testing the integrated prototype.

4.5.3.3 Conclusion

This test indicates that the elastomer buffer developed in this thesis also performs well when integrated into a wearable prototype. This shows that the concept is viable as a means of reducing vibration exposure.

4.5.4 Muscle exertion test

For the validation of the concept it is important to verify whether the prototype allows the user to handle the power tool with less muscle exertion in the hand and lower arm. As listed in 3.7.3, in the hand-arm system two functions involved in the act of holding the are tested here:

Right hand (total)	**Hold (make connection)**	**grab / clamp down**
Wrist	Hold tool upright	Exert moment on handle

Ideally this test is done using an EMG test, that measures muscle activation. However, in conducting this test the equipment failed. Due to feasibility considerations an EMG test will not be part of this thesis. However, testing the prototype, purely based on experience can give some insight into whether the prototype reduces muscle exertion.

holding the power tool with the prototype is compared with plainly holding the power tool in the hand. It is noticeable that simply grabbing the power tool adequately with the hand requires considerable clenching of the hand. Keeping the tool upright is also a noticeable exertion (figure 77).

Figure 77. The power tool is held with one hand.

When holding the power tool using the integrated prototype, the hand is flexed considerably less than when holding the tool directly (Figure 78). What is noticeable is it is necessary to hold the hand in a stiff position for the prototype to maintain a tight fit on the hand. This means some exertion in the hand is noticeable. With regard to holding the tool upright, the wrist support offers some relief, although it is difficult to transfer the force onto the wrist support. With a tighter fit of the wrist support around the wrist this could be easier.

Figure 78. The power tool is held with one hand using the integrated prototype.

4.5.5 Conclusions

From this experiment can be concluded that the prototype likely does reduce muscle tension in the hand-arm system while holding a power tool. Using the prototype does introduce a new source of muscle tension, which is to adequately connect with the prototype. This can be countered by a tighter fit of the prototype to the hand, which will likely also improve the performance with regard to holding the tool upright.

An EMG test with multiple test subjects is still needed to verify and quantify these results, but this test indicates that there is likely a positive result to be found.

4.6 Product vision

The prototyping process up to this point has been to explore the basic functionalities of a working product. Obviously the current prototype is not fully usable, and several functionalities still need to be developed. This paragraph is about offering a vision of how to full fill these functionalities and how the protection device could be used as a fully functioning product.

During the development described in this thesis a product vision has taken shape of how to solve these remaining issues towards a fully usable product. However, to explore these functions in depth by means of prototyping or otherwise would be too extensive for the scope of this graduation project. The remaining necessary functionalities of this product vision will therefore be explored in the form of illustrations. These illustrations portray a possible design of how to fulfil these functionalities, and are not meant as definitive designs. Instead they are meant to show a feasible way of realising these functionalities, while keeping the relevant design requirements in mind.
The final prototype is taken as a starting point for this process, shown in Figure 79 as an illustration. This rendition also includes several minor adjustments to the shape of the buffer that are meant to make the device more easy to use.

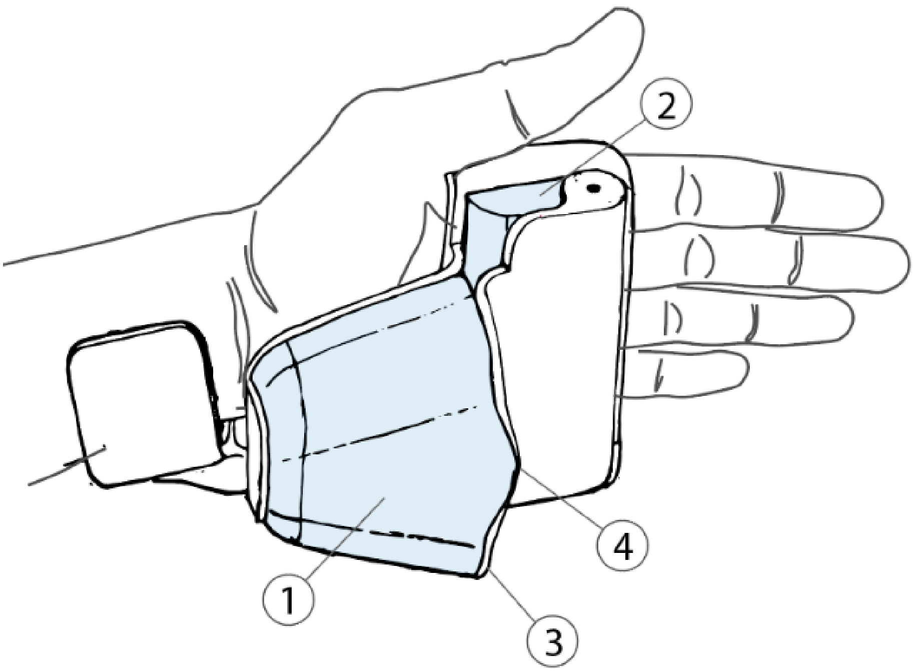


Figure 79: the envisioned hand mounted buffer, as a basis for adding the other needed functionalities in the product vision.

Particularly, the outwards facing corners of the main buffer have been rounded to avoid unwanted snagging, as described in requirement 6.3. Instead of the corners the middle has been flared up to stop the tool handle from sliding off.

4.6.1 Grabbing mechanism

The grabbing mechanism is a subsystem of the protection device that provides a mechanical connection to the power tool. Specifically, the grabbing mechanism addresses the following requirements:

With regard to usability:

2.2 The product must fit/be adaptable to different power tools.

2.3 Should be intuitive enough in use, so that any worker can learn to use it in a single session.

With regard to vibration mitigation:

3.1 Should reduce muscle exertion of the hand and arm.

Picture 80 shows the proposed grabbing mechanism, which consists of two separate 'fingers'. Closing the hand wraps these fingers around the power tool handle. Because the users' hand needs to be mechanically isolated from the power tool, the grabbing mechanism then holds the power tool independent from the hand, by means of a locking system. The hand can now be relaxed, while the power tools weight held by the grabbing mechanism.

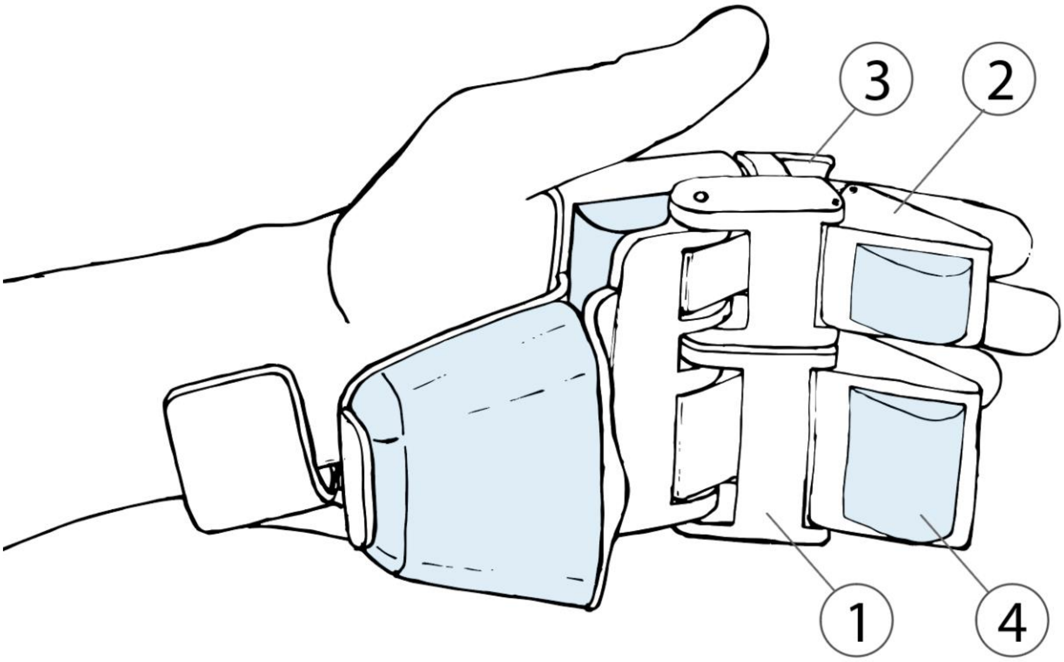


Figure 80: The grabbing system added to the hand mounted buffer.

The two fingers function independently. This makes it possible for the lower finger (1) to primarily hold the weight of the power tool, while the upper finger (2) is pressed to engage the power tool trigger. By moving the fingers all the way back, the 'quick-release' lever (3) is engaged which releases the grip from the power tool handle. Elastomer pads (4) are added for pressing on to the handle, for better grip and contact surface.

The grabbing mechanism lock onto the power tool handle using a rachet mechanism (Figure 81). The mechanisms' finger is pressed down by the user(1). the pawl(2) presses on to the rachet wheel by a torsion spring, and stops the mechanism from opening. The users presses the grabbing mechanism as far closed as needed to form a solid connection to the power tool. By fully opening the hand the user engages the lever(3) that in turn disengages the pawl. Under pressure of a second torsion spring (4) the grabbing mechanism opens and releases the power tool.

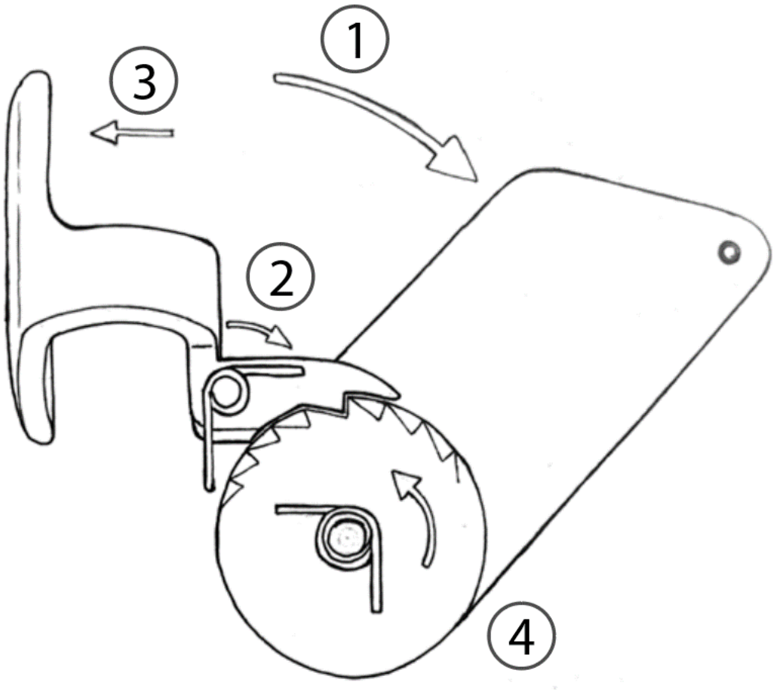


Figure 81: The locking mechanism and how it functions.

The 'fingers' of the grabbing mechanism wrap around the power tool (Figure 82). The upper parts' (1) rotation is dependent on that of the lower part (2), due to the connecting bar (3), and the reciprocal positions of all the rotation points. This mechanism ensures an enveloping movement of the finger as a whole, as a direct result of actuating the lower part.

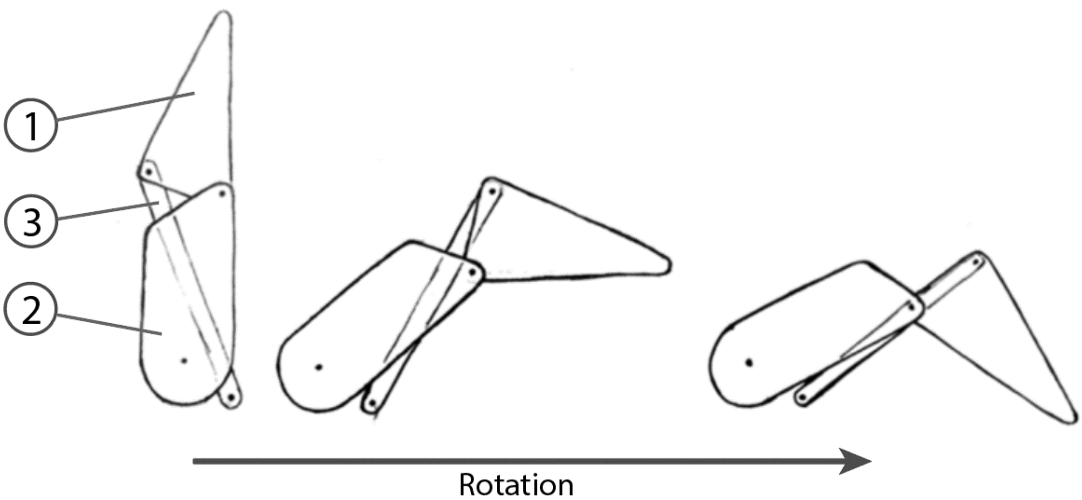


Figure 82: The rotation of the grabbing mechanism.

4.6.2 Glove

For the device to be worn and used, it is important to fit the protection device to the hand tightly enough, to provide a stiff and reliable connection to the power tool.
In the presented design in Figure 83 the palm-mount and the wrist-support remain hard plastic parts (colored red). a glove has been integrated to make it more comfortable to wear and to provide a way to fit the plastic parts tightly to the wrist and hand.

Two places on the device are considered to especially need a tight fit. Around the palm and back of the hand (1) to support the weight of the power tool, and around the wrist (2), to tighten the wrist support (3).

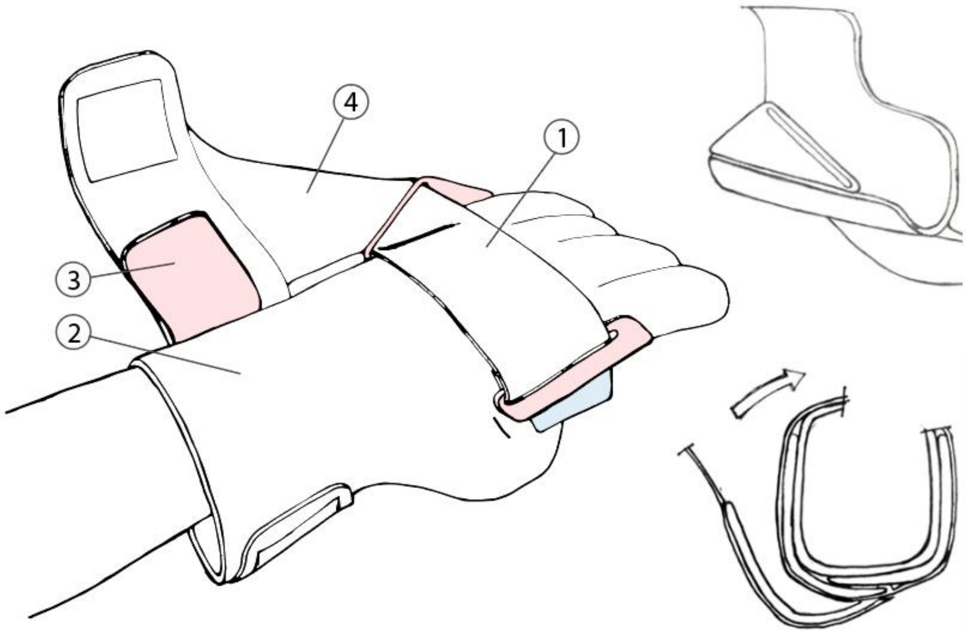


Figure 83: The glove and straps opened.

For ease of use these two places are tightened using a single combined strap (4). In Figure 84 can be seen that this strap closes the wrist support around the wrist(1), and tightens the other strap that runs across the back of the hand (2). In doing so this strap is pulled diagonally from the bottom of the back of the hand to the top of the wrist (3). Two functions are achieved this way: The palm frame is strapped onto the hand tightly and secondly, the palm frame is pulled back onto the base of the thumb by the diagonal strap. This further provides a tight fit.

When the strap is wrapped around the wrist, it tightly closes the glove around the wrist. The strap is then held in place by a Velcro pad on the inside of the wrist.

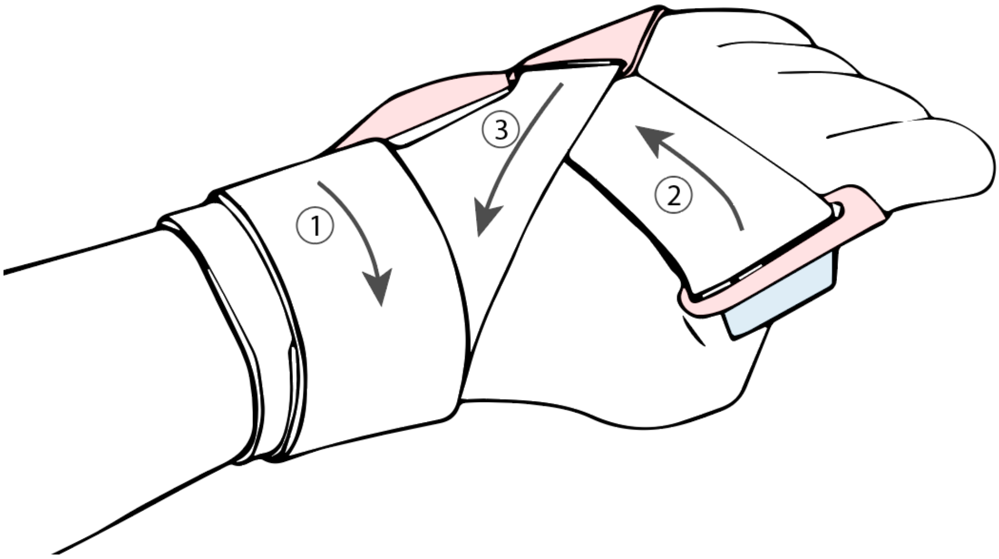


Figure 84: The glove closed.

4.6.3 Adjustable stiffness

According to requirement 1.2, the protection device should in no case increase vibration by means of resonance. Any object, and so also any possible design for a vibration isolator, has a resonance frequency. A method of adjusting the resonance frequency of the isolator can offer a solution to this problem.

As seen in Figure 85, a rotary dial (1) is added to the outside of the elastomer buffer. This dial can be used to apply pre-tension in the elastomer buffer, changing the stiffness, and so the resonance frequency. When significant resonance (and vibration amplification) is detected, the resonance frequency can be changed to reduce this amplification.

Presumably the dial is does not have to be adjusted often, only when changing tools or when working a different material. For this reason the dial is designed not to protrude too far from the main shape, instead for ease of access.

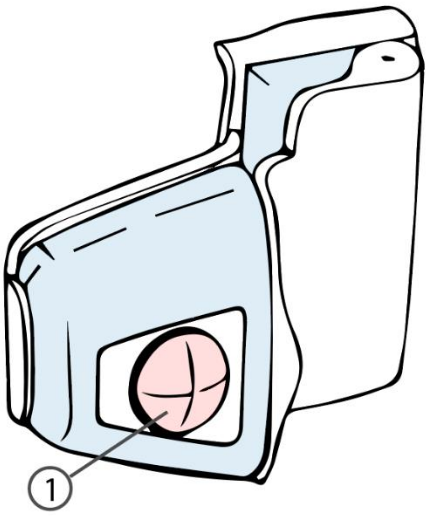


Figure 85: A rotary dial to adjust the buffer stiffness.

As seen in figure 86, the dial (1) engages two gears on either side (2). These gears rotate a threaded bolts (3), that both pull in a plate on opposite side of the buffer. When the buffer is put under pressure by using a power tool (4), the buffer has a diminished ability to bulge outward (5) depending on how far the dial has been rotated. As discussed in 3.9.1.2 this changes the effective stiffness of the buffer.

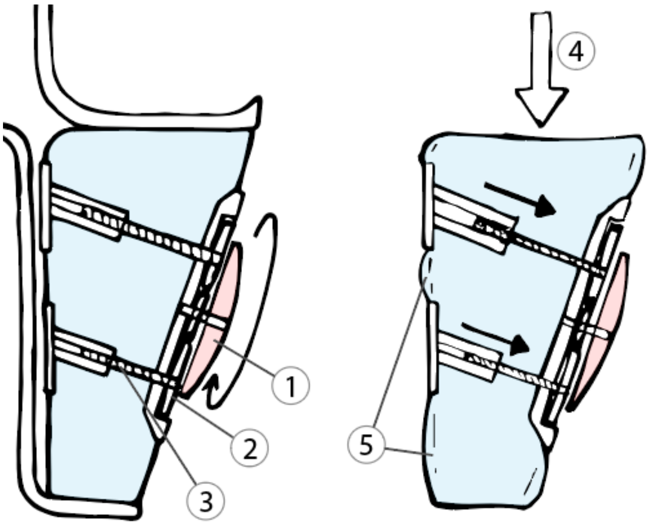


Figure 86: A cross-section of the adjustment mechanism.

4.6.4 Logging system

An important part of the envisioned function of the protection device is to provide insight into the vibration exposure. To perform this function sensors embedded in the protection device are needed. This is to avoid the situation where the logging system is dependent on the declared vibration emission of the power tool, as seen in the existing logging system (see paragraph 3.10.3).

The logging system addresses the following requirements:

4.1 Should monitor and communicate vibration duration and severity.

4.2 Data must be independent of declared vibration emissions (real time monitoring).

As seen in Figure 87, two accelerometers are embedded on either side of the buffer in the palm area. The sensor on the outside (1) is pressed up against the power tool handle during use and measures the emitted vibration (in accordance with requirement 4.6). The sensor on the inside (2) is pressed against the palm of the hand and measures the vibration exposure.

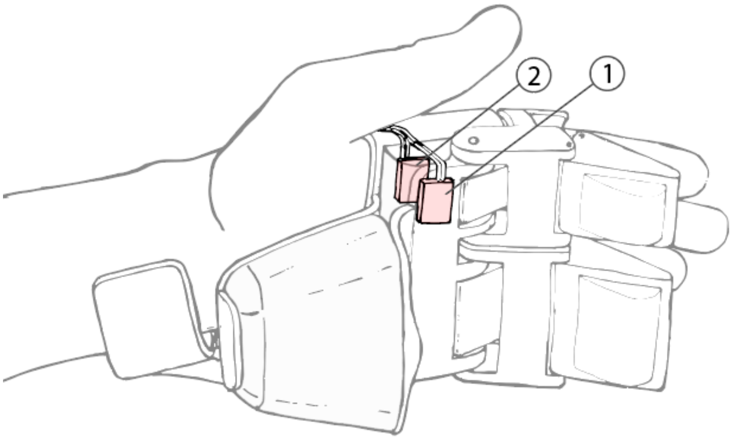


Figure 87: The sensors embedded in the palm on either side of the side buffer.

As seen in Figure 88 the display is embedded in the glove behind the thumb (1), making it easier for the user to keep track of their vibration exposure. While holding the power tool, the

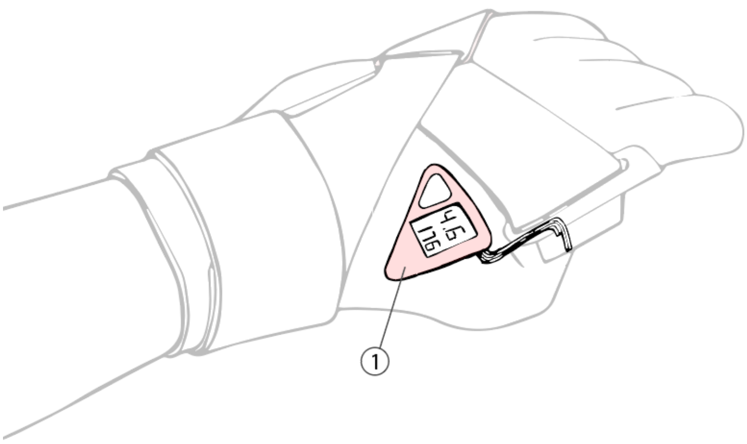


Figure 88: The display providing information related to the measured vibration exposure.

On the display the following information can be shown:

- Duration and magnitude of measured exposure.
- Time until maximum daily exposure is reached.
- Vibration reduction measured.
- Advised adjustment to the buffer.

4.6.5 Final vision

As seen in Figure 89, the final concept including all the afore mentioned functions.

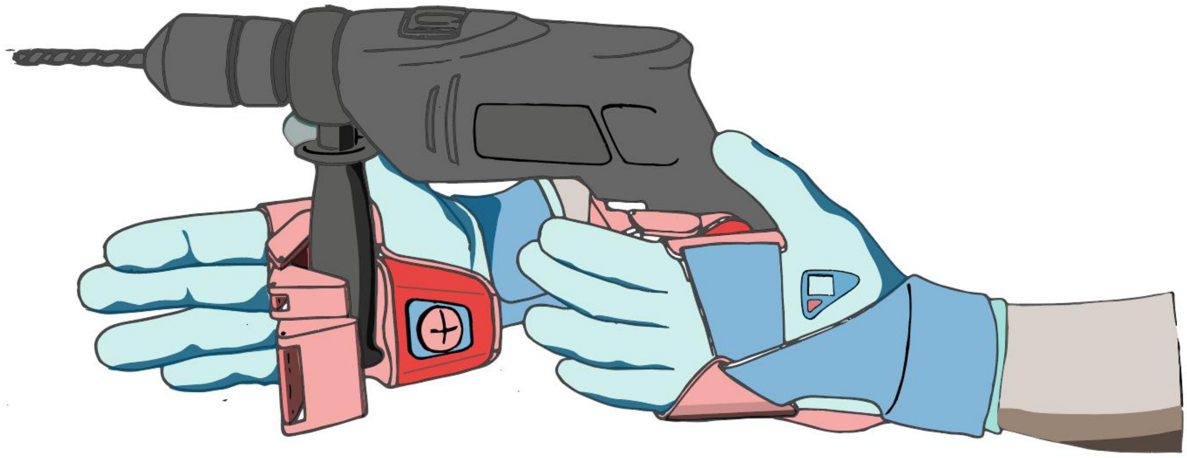


Figure 89: The protection device in use, worn on both hands.

4.7 Concept evaluation

4.7.1 Accomplished value

The concept developed in this thesis is designed to address the requirements that were listed as a result from the analysis. The most important requirements are listed again below, with the corresponding solution present in the developed concept.

Requirement number:	Requirement description:	Solution:
1.1	Must increase worktime by 50%.	Achieved by the elastomer buffer, developed in the second experiment (paragraph 4.3.7)
1.2	No possibility of increasing vibration by resonance.	Achieved by means the buffer adjustment mechanism (changing resonance characteristics) and by the two sensors of the logging system (remove protection device in case of amplification)
1.6	At least applicable to the power drill configuration, and other tools that have a pistol grip.	Achieved by means of the grabbing mechanism (coupling), and by the buffer adjustment mechanism (effective damping).
2.1	Should not significantly impede freedom to manoeuvre when holding a power tool.	Achieved by the fact that it is a hand mounted protection device. Manoeuvrability is somewhat diminished by the wrist support.
2.2	The product must fit/be adaptable to different power tools.	Achieved by means of the grabbing mechanism.
3.1	(Wish) Should reduce muscle exertion of the hand and arm.	Achieved by means of the wrist support (holding the tool upright), and by the grabbing mechanism (gripping).
4.1	Should monitor and communicate vibration duration and severity.	Achieved by means of the logging system. The display informs the user of relevant information. The data of multiple sets can give company-wide insight on vibration exposure.
	Data must be independent of declared vibration emissions (real time monitoring).	
	(Wish) Should provide oversight on a management level by providing data on vibration exposure.	

The real accomplished value of this design is that it solves principle problems of isolating the hands from vibration sources, while simultaneously allowing the user to handle their power tool intuitively and adequately. In addition the user gains more insight into their actual vibration exposure, due to the real time vibration monitoring.

4.7.2 A need for concept validation

The design presented in paragraph 4.6 is quite a leap from the prototype developed in this thesis, but can help explore what still needs to be solved to develop the prototype into a fully functioning product. To develop the current concept further towards a successful product, it needs to tested by users in the field. Ultimately only cooperation with these users and construction companies can provide the needed validation of the concept.

Especially design features that focus on the user experience are valuable to explore in this regard. For example the point of stability: providing a stiff connection between hand and tool is evidently an important issue. But questions like how stiff this connection needs to be, and what compromises between stability and vibration mitigation are appropriate, are difficult to answer without a field test.

The grabbing mechanism is another example of this. It is designed with intuitive use in mind. It provides a stiff connection, and allows the user to use the power tools trigger. But these functionalities have come at the expense of a complex mechanism with many moving parts, while the a quick release mechanism is needed for the safety of the user. Testing with actual users will likely answer many questions about whether this system will work as intended, and whether these functionalities are worth having such a complex system.

4.7.3 Challenges in design

during development several challenges regarding the design have come to light that deserve mentioning, and need to be addressed in further development.

- In use the protection device is also an extra pair of gloves that the worker has bring and put on before picking up the power tool. in work activities that require allot of switching between various manual jobs and actual 'trigger time', this might pose a serious problem for product acceptance. regardless of the need of vibration protection, workers might not be enthusiastic about protection gear that introduce another step in their work. In activities where trigger time is relatively uninterrupted, this might be less of a problem. especially when working with tools that have particularly high vibration emissions.
- Despite the quick-release mechanism, there is a possible danger of getting stuck to the power tool without the ability to release. To rely on a mechanism for safety is not a desirable situation. From a design point of view there is the obligation to consider that any mechanism can fail, especially in regard to requirement 6.2 (Should not be able to become a safety hazard by contamination of dust or sand).
- The grabbing mechanism itself is rather complex, which means that it is more likely to fail. A simpler design in this case is desirable, leading to a more reliable product.
- The logging mechanism can be another way in which workers are monitored by the company management. this can lead to undesirable situations with regard to privacy. In further development, it is important to keep in mind that the data that is gathered must not undermine the position of the worker.

5. Recommendations

Based on the design and analysis described in this thesis, several recommendations can be made towards further development of the concept. This is in addition to the most important recommendation of pursuing concept validation by user test as discussed in paragraph 4.7.2.

5.1 Recommendations from design

In further developing the design the following points are recommended:

- Further develop embedded safety measures such as the quick release. These should be as simple and reliable as possible, especially after extended periods of use and contamination with dust and sand.
- Further develop for a less complex and cumbersome grabbing mechanism. If the locking system remains a safety issue it might have to be replaced by another solution.
- Further explore different geometries in development of the elastomer buffers, to reach better performance with regard to stability and vibration absorption.

5.2 Recommendations from analysis

Aside from the recommendations resulting from the design, the analysis done on hand-arm vibrations has also led to several valuable insights. Because the continuation of this project will be in the form of a start-up, these insights have been translated into either opportunities or challenges with regard to this start-up.

Conclusion	§	Opportunity	Challenge
In some other EU countries better data is available on hand-arm vibrations than in the Netherlands, or the European Union as a whole.	3.2.1	Better data from other countries provides a useful comparison to the Dutch data, which helps to argue the case that more attention to hand-arm vibrations is necessary.	
Hand-arm vibrations is a significant problem in the Dutch construction industry.	3.2.2	Makes it easier to develop, test and launch a product since the domestic market is likely to be suitable.	
Hand-arm vibrations is a phenomena spread across a multitude of professions within construction.	3.2.2		Makes it harder reach the consumer, as the end users are a more diffuse group.
Safety is a constant issue in construction.	3.3		Makes it difficult to raise awareness for hand-arm vibrations, when other, more obvious hazards are not yet addressed adequately.

Hand-arm vibrations is a problem that greatly burdens the healthcare system and therefor society.	3.4	Makes the protection device a preventive measure for a serious health issue. An opportunity for funding from medical institutions.	
It is difficult for workers to avoid being afflicted by HAVS.	3.4	Makes the protection device indispensable for construction workers. An opportunity for co-operation and funding from labor unions.	
No individual stakeholder has the ability to solve the problem of Hand-arm vibrations.	3.4	Makes the protection device a possible solution that no other party can offer.	
The inspection has several other safety hazards as a higher priority that hand-arm vibrations.	3.5.1		Makes it more difficult to argue for the necessity of the protection device. Means less incentive for companies to adopt it.
The regulation values of 2,5 and 5m/s^2 are very low values, which are difficult to not exceed.	3.5.2	Makes any anti-vibration measure indispensable (especially when able to use in tandem with other anti- vibration measures).	
Vibrations within a single measurement are a complex combination of a range of frequencies in x y and z directions.	3.6.2	Makes the logging system very useful, when able to make complex data comprehendible.	Makes the vibration data in development more difficult to analyse. Consequently makes it harder to develop an effective vibration damper.
percussive power tools emit frequencies mainly below 50Hz.	3.6.2	Makes it easier to develop a vibration damper, as these power tools have comparable vibration profiles.	
Hand-arm vibrations is a problem that greatly burdens the healthcare	3.4	Makes the protection device a preventive measure for a serious	

system and therefor society.		health issue. An opportunity for funding from medical institutions.	
Prolonged vibration exposure causes neurological and vascular diseases.	3.8.1		
Returning to working with hand-held power tools after recovery quickly brings back symptoms.	3.8.4		
Anti-vibration technology is an improvement but does not change anything fundamentally.	3.10.1	Means another vibration mitigating measure is necessary.	
Anti-vibration gloves are only marginally effective.	3.10.2		
No significant means of protection is currently available.	3.10.9		
Vibration gloves must not exceed a thickness of 8mm.	3.5.4		Considering that these requirements are incompatible with the developed concept, this could mean that the protection device cannot technically be defined as a ‘glove’.
Vibration glove must cover the whole hand and fingers.	3.5.4		

6. Project continuation: towards a start-up

6.1 Value proposition (raison d'être)

The main value of the product is the first protection device that makes a significant difference in reducing vibration exposure. Without this, adhering to the vibration limits as defined in regulation means having to take enormously unproductive measures (as explained by Wibo Feenstra, appendix 1). For companies it now makes sense to address hand-arm vibrations, because now at least there is a possibility for a good outcome: Adhering to the vibration regulations <u>and</u> working productively.

6.1.1 Strengths

As listed below, the strengths the protection device offers to companies and workers:

- Only protection device available that can offer a high percentage vibration reduction. Especially for activities where people are exposed to high vibration emissions for extended periods of time, this protection device can make a significant improvement.
- gives companies something to address hand-arm vibrations without sacrificing productivity.
- Gives insight into vibration exposure, specific to the individual worker. Gives oversight into companywide vibration exposure linked to individual tools, activities and employees.
- Because it is a protection device adaptable to various tools, it can always be used in tandem to other vibration exposure mitigating measures(e.g. power tools with embedded anti vibration technology, using sharper tools bits, reducing exposure time).

6.1.2 Weaknesses

As listed below, the weaknesses the protection device offers to companies and workers.

- Yet another implement that has to be used, addition to the power tool itself and other protective gear. In combination with low awareness of hand-arm vibrations, this might cause workers to neglect the device
- It is different from what employees are used to. Especially not directly holding the tool is a new concept that workers might be reluctant to adopt.
- Hand-arm vibrations remains an underappreciated problem, both by companies and in enforcement. This means they are less likely to adopt a protection device that specifically addresses hand-arm vibrations.

6.2 Product development roadmap

The process described in this thesis is a solid step towards developing an effective protection device against hand-arm vibrations, but a successful capitalisation of this protection device as a product is still far away. Building a viable start-up and bringing it to fruition is a challenge all on its own. The steps necessary to reach this goal are outlined in a roadmap shown below in Figure 90.

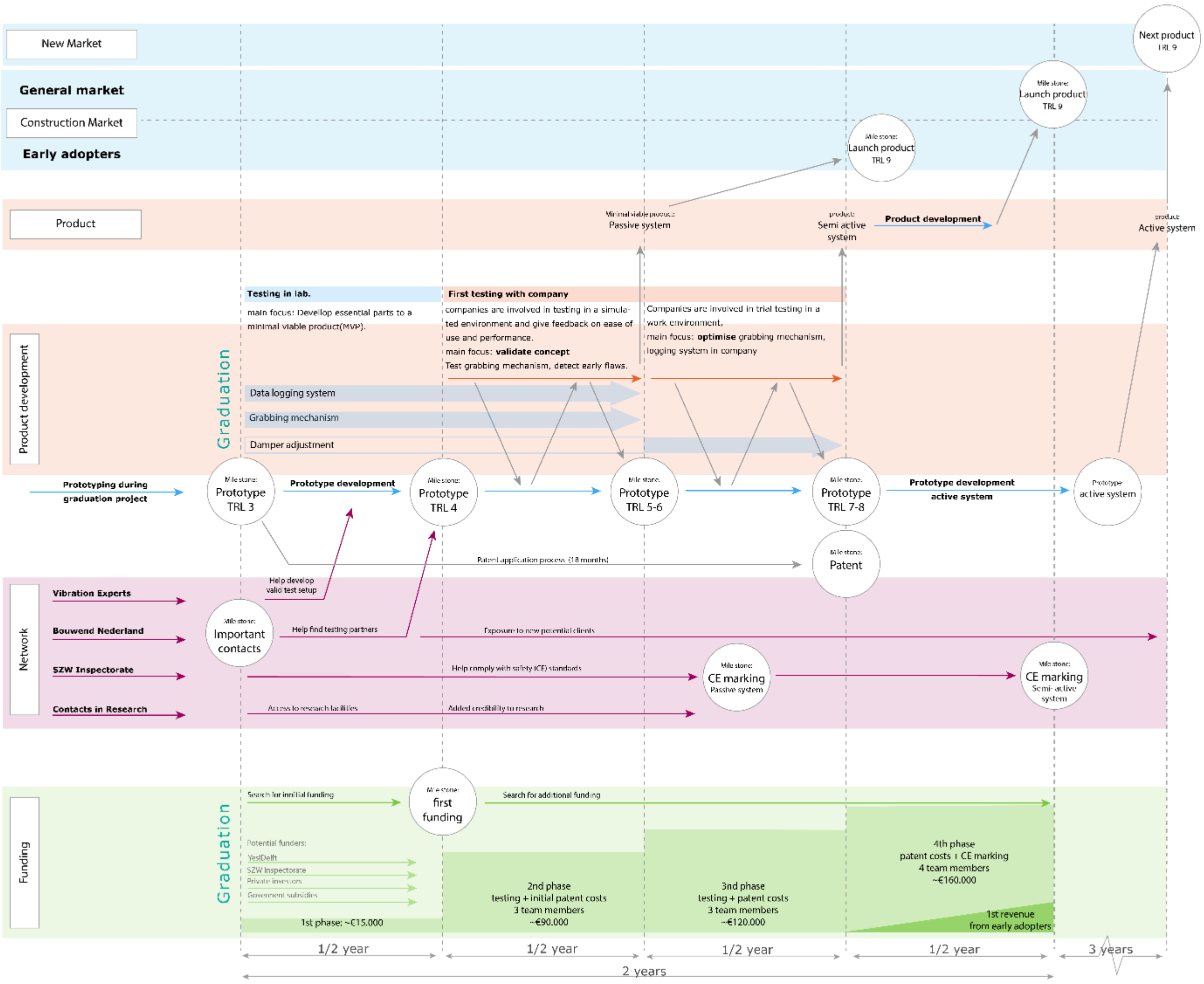


Figure 90: The roadmap, describing a detailed plan of bringing the current concept to product launch, and thereby creating a successful company.

7. Project evaluation

This project based on a self-initiated subject proved to be complex and difficult to manage in many regards. Conducting the initial research was challenging but varied, as many different topics where involved. this made hard to find a suitable direction to take the project in. Based on the research I had done in vibration mitigating technologies, I was stuck on choosing what technology to apply. What proved to be a more suitable direction for the project, was to focus on one simple technology, and to work on proving the viability of this technology.

7.1 Oversight

Keeping oversight with regard to the project was also difficult. Especially after the analysis phase, it was difficult to see where the project was going. It would have been better to have a clear scope, to what point to develop the concept. I expected to only do a short process towards designing a concept, but ended up doing much more prototyping and designing than I could have foreseen, and so the project turned out to be much more extensive than I initially anticipated. knowing this from the start would have helped to plan the project better.

7.2 Covid

Due to the pandemic restrictions it was more difficult to get into contact with people. Even though I gathered several valuable contacts. The most significant impact this had on my project was that I had no hope of doing some kind of validation with users in the field. As a result much of the concept still needs to be validated with users. Especially with regard to founding a startup, validating the concept is essential, and I would like to have included that in my project.

Although I usually enjoy working alone, doing a graduation project during the covid pandemic has taught me that regular contact with people is important for my work. It would have been very helpful to discuss my project with other students, as well as hear about how other people manage their project.

7.3 Design methods

The design methods I learned during my education at the faculty of Industrial Design have helped in the design process, but I noticed that they didn’t help me as much in finding what I at that time needed: the right design direction. What did help was finding the right framing of the solution space, and for this I had no established methods available yet. This did teach me to pay more attention to the concept of framing.

Further in the project, I continued designing by means of prototyping. this was a much more fruitful and intuitive process. In which I managed to make a lot of progress. For example the of hand positioning and developing a wrist support where design processes that where much more intuitive.

7.4 The experiment

setting up and conducting an experiment was also challenging. It was a difficult process of finding a test setup that would be simple to build and yet yield simple useful results. Ideally I would have used a test setup as described in a scientific paper, but it ended up being necessary to design my own test setup. It took much consideration to realize that the established methods would not suffice.

In addition to this, I had little experience in proper scientific reporting of the results. To document the findings in a clear and complete way was difficult. Also interpreting the results was challenging. Also determining the right outcome measures was challenging as a vibration has several variables and which would be important for my analysis.

8. Personal reflection

Although I think that in hind sight I could have done many aspects of this project better, I think I have made great progress in learning to manage a large and complex project.

8.1 With regard to skills

I am pleased to have learned so many new distinct skills (3D printing, silicon molding, working with sensors, Matlab, working with Illustrator) as well as things like the technical aspects of report writing. I also got to apply methods I learned in my entrepreneurship electives with regard to contacting people. Gathering information and managing these contacts was very useful. I learned to set up an experiment from the ground up. From determining what I needed to know, and how to test that, to designing a test setup that would yield simple but standardized results, to interpreting the results.
I learn to persist and continue, even when there was no apparent end in sight for the project. By trusting that through the quality of my own work the project would eventually come to a good end.

8.2 With regard to communication

I learned that it is quite a skill to clearly and accurately communicate ones ideas. Especially when you are heavily invested in the project and think of nothing else, it can be difficult to reduce those ideas to their basic concepts, and explain them to other people.

Throughout the project I learned to use the coaching meetings better. I learned to determine before hand what information I would need to continue, and to make sure to get that input from the meeting.

I found it very difficult to document my process and ideas in a structured way. This ended up being a major obstacle in my project, for which I needed a lot of help to overcome. This project has been an enormous exercise to improve my skills in this regard. I now have a much better view of what is needed and how much effort is involved in accurately communicating ones ideas so that they may be understood. I also now have a much better grip on handling such a problem in the future.

8.3 With regard to planning

Especially because this project lasted so lang, I ended up going through many cycles of planning. This has given me much more experience in planning, both on the long term and the short term. I have learned to appreciate the value of a planning that outlines the scope of the project, which I lacked during a large portion of the project. Also weekly plannings where useful. They helped keep pace and make steady progress. Planning a days work helped utilizing the hours of the day in which I was most productive.

While being isolated due to the pandemic restrictions, it was hard keeping a steady daily schedule. Where in a normal year I would go to the faculty to work, most days I had nothing to plan my day around.

8.4 What I take from this project:

I am proud of having managed my own initiated project, based on my own analysis and design that now has materialized into something that is starting to resemble a credible solution to a real life problem. The value of this project is still built on having recognized a problem that is very much worth solving. When I again recognize a problem this way in the future, I will have the confidence to pursue it like a new project, and work towards designing a solution.

I have come away from this project with a much more abundant set of skills, by having managed it in all its aspects. I have also come away with a renewed love for prototyping. I enjoyed coming up with ideas and turning them into something tangible. I aim to continue on to seek new challenges in my work as a designer.

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Msc. F. Hulzinga

10. Glossary

1. HAVS – Hand-arm vibration syndrome. The umbrella term to describe all pathologies that result from hand-arm vibrations.
2. HSE – Health and Safety Executive. A British government agency responsible for the regulation and enforcement of safety in the workplace.
3. VWF – Vibration White Finger. Also known as Raynaulds Phenomenon. Blanching of the fingers by reduced blood flow as a result of vibrations.
4. Incompressible solid – A material that keeps occupying the same volume when it is deformed.
5. PPE – Personal protection device. An implement that is worn to protect the wearer of safety hazards.
6. Declared vibration – The vibration emission a power tool manufacturer declares in the tools manual.

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a.

Appendix 1

Interview Wibo Feenstra
Interviewed on 7-01-’21 about his knowledge of HAVS, safety culture in construction work, and the notion of collection data on vibration exposure.
Wibo Feenstra is a safety expert with Construction company group Van Wijnen.

anecdote:
“I know a concrete driller who developed severe HAVS after the 45 years of work in construction. The use of his hands was severely diminished. Obviously he was entitled to a hefty compensation, But without that knowledge, and perhaps out of loyalty to his former employer, one might be reluctant to file damage claims.”

Difficulty of dealing with regulations

Indeed it can be difficult to stay with regulation limits with regard to vibration exposure. The Inspection service in this case does not provide much means to deal with this problem.
So for example: Say a job requires the use of a kango (a powered break hammer) for 8 hours total, and in complying with regulations this machine can only be used for something like 2 hours. The clients would then receive a bill that shows the cost of hiring 4 people for that day. It is obvious that this isn’t a viable way to address the problem.

on the use of sensors to collect data with regard to HAVS:

The use of vibration sensors can help bring insight into the work conditions for both the company and the worker, and can make the problem quantifiable. However it can also lead to a policy of maximizing the work time, and thus vibration exposure, up to the exposure limits.
Keeping track of exposure to individual workers, creates the possibility of documenting this exposure in their personal file within the company. When later in his career the worker does develop HAVs symptoms, At least there will be some documentation.
In the case that completing a job within reasonable time requires a worker to exceed exposure, at least this can be a conscious decision. This way the worker can be made aware of the risks, and be given a choice on whether to do the job.

On the adaptation of new protection gear:

When workers are expected to use a certain protection device, there is supervision on site to make sure that they in fact are made use of. So in this sense the company has some control over their employees using protection gear. But workers in the construction industry can be conservative when it comes to their way of working. They can be reluctant to change their methods, and when it comes to doing their job, any protection gear that forms an impediment to getting the job done is often left aside. This way workers can sometimes make choices that are not in their best interest.
In contrast to this they can be eager to adopt new equipment to the newest version, in the sense that they seek out the newest and the best of a particular machine.

Appendix 2

Profession (in Dutch)	Number of practitioners (Netherlands)	Percentage reporting hand-arm vibrations
Using percussive powertools:		
Betonboorder	300-500	49%
Beton reperateur	800	50%
Beton timmerman	13K+14K	28%
Grond bewerker	17K	28%
Koppensneller	-	42%
Ovenbouwer	300-400	36%
Using compactors:		
Stratenmaker	10K	40%
Vakman GWW	3K	30%
Rioleerder	2-4K	31%

Appendix 3

Maroesja Bonsen, Ergonomics specialist at the SZW Inspection

The SZW Inspection performs inspections and enforces regulation, and in principle does not provide advice to companies. The Inspection Service is priority driven, meaning that special attention is given to several safety hazards: 1. Falling from heights, 2. Lifting and pushing heavy loads. These safety hazards tend to cause the most injuries, and are also easy to identify as the main cause of a possible injury. In the case of hand-arm vibrations, it is difficult to prove any case of over exposure, and even more difficult it identify this as the main cause of an injury. Up to 2014 there is only one case known with the inspection of someone claiming injury from HAVs.

There is a definite need for more insight into the problem of HAVs. HAVs is definitely on the radar of the Inspection Service but is the regulations are not enforced much because it currently is of a much lower priority and the inspection capacity is very limited.

In principle the needed expertise is present in the Inspection service, but violations are hard to identify. Also doing a proper vibration measurement is difficult, and the Inspector has no choice but to take the declared vibration emission of the power tool in question at face value. The inspector can in some cases request the company to hire an expert to do a vibration measurement of a particular work situation.

When an inspector visits a company, the entire inspection usually has to be done within an hour. This means that there is not much time available to focus on one particular situation, and more imminent hazards will get priority.

When a violation of vibration exposure limits is determined, one of two things can happen. In case of exceeding the stopping value, the inspector will require the company to cease the work activity on the spot, and a fine is given. The work activity can only be recontinued when the company can prove that the exposure limit is no longer exceeded to an inspector after a certain period. Continuing the activity regardless is considered a criminal offence. In case of exceeding the action value, the work may be continued but the inspector will demand a change of the work situation within a given time. This can involve purchasing a protection device.

The consequences of HAVs might not be as immediate as those of a fall, but can be especially corrosive to society. Work disability as a result from HAVs tends to be for a long period of time, or even permanent.

With regard to a protection device: When a protection device for a certain work hazards is available, with at least two available brands, it is therefore also demanded to be used by the inspection. A unique protection device only offered by a single brand cannot be demanded as this would cause a government backed monopoly. In this case the protection device can still be included in the Labour Inspection catalogue, and be recommended by the inspector.

bringing more insight into the problem and providing data is much needed. the Branche organisations can be of much help in this regard. Doing research through these organisations is can be much more efficient. The companies are more willing to cooperate with these organisations. The branche organisation already do conduct research into work safety in their member companies, and have a intrinsic interest in the relevant safety issues. When the branche organisation can prove to the Inspection that a certain work hazard is not a great problem, the inspection can reduce enforcement on that issue.

Appendix 4

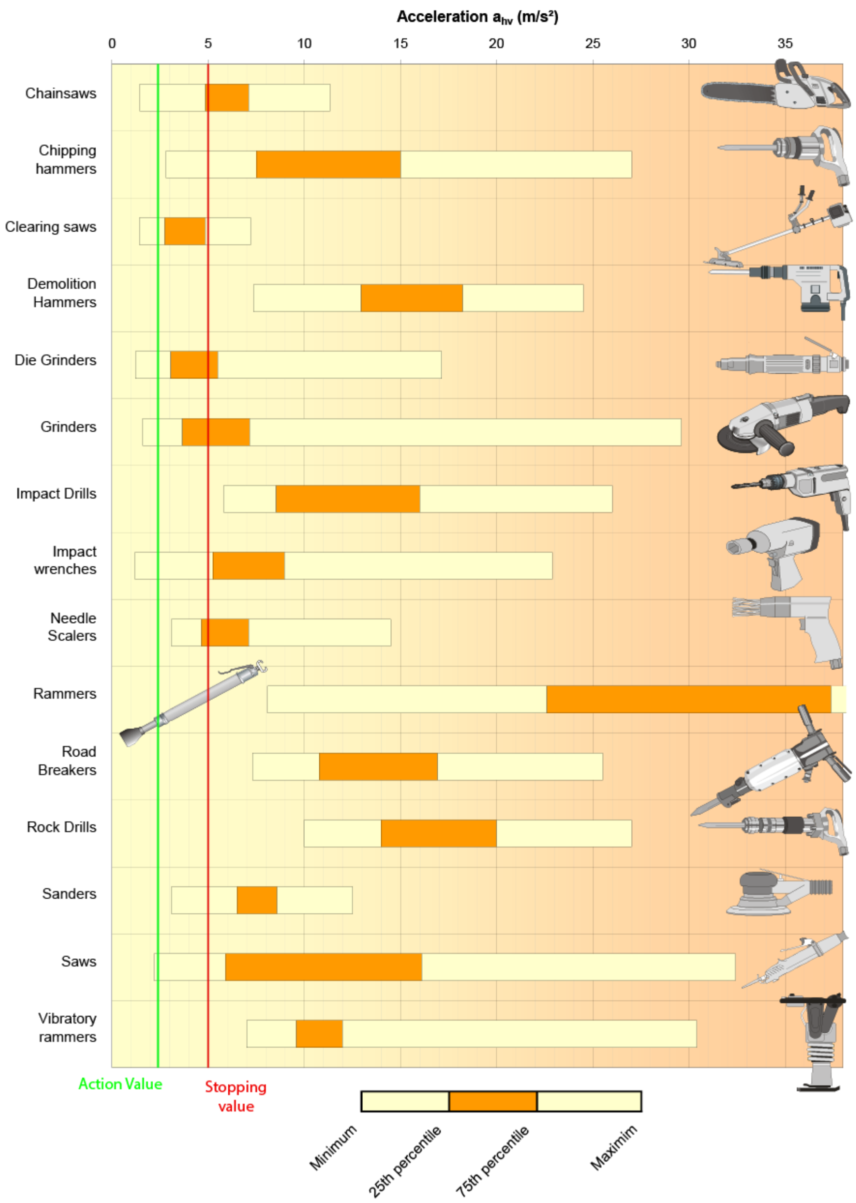
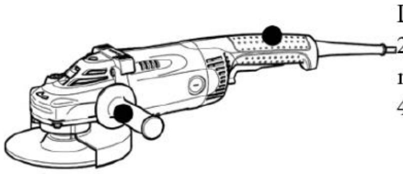


Figure 2 Examples of vibration magnitudes for common tools

Ranges of vibration values for common equipment on the EU market. These data are for illustration only. For more details see Annex B.

Appendix 5

Angle Grinder



Declared vibration emission:
2,5 m/s^2
measured vibration emission:
4-11 m/s^2

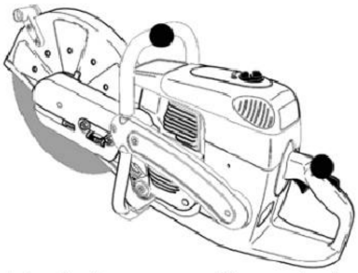
A tool to either cut or polish an object, depending on the disk used. The user holds the tool steadily with two hand. One on the base and one on a side handle close to the rotating disk. The exerted force of the user on the tool is typically light, but is used with precision, especially when cutting. The tool can be used on any hight the user can comfortable reach, usually on table hight or near ground level.

Belt Sander

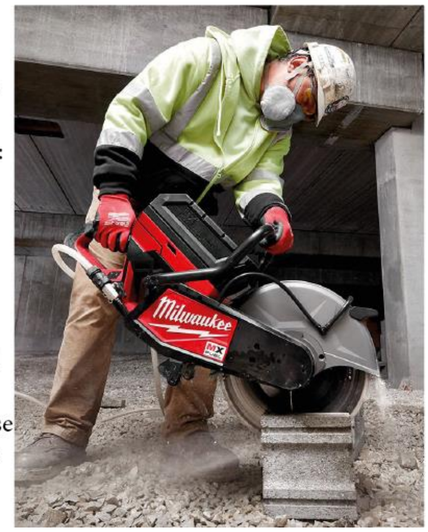
Declared vibration emission:
2-9 m/s^2
measured vibration emission:
2-9 m/s^2
Typical duration of use per day:

This tool is mostly used on table hight and usually the tool rests its weight on the work piece. The worker hold the tool in a 'pistol grip'. Often pressing down and in so adding pressure while moving the tool across the work object. Because the sander is used on table hight the worker often works in a slightly stooped posture to be able to exert extra force on the tool. The belt sander typically emits high frequency vibrations.

Stone Saw



Declared vibration emission:
4-8m/s^2
measured vibration emission:
3-9 m/s^2
Typical duration of use per day:

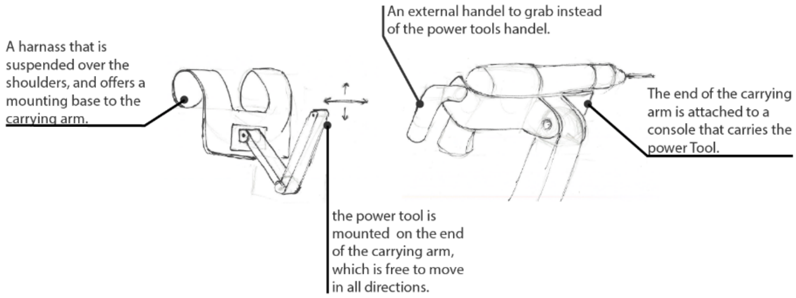


This tool often powered by a petrol engine, and is a heavy hand-held tool. Because of its excessive weight the tool is mostly used close to the ground. The user does not need to use a lot of force since the close to ground use, but does have to manoeuvre its heavy weight in order to guide the saw precisely.

Appendix 6

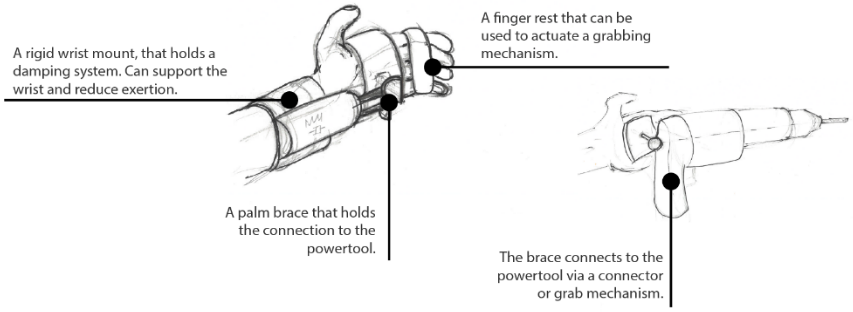
1 User centred, torso supported

A wearable harnass functions as a mounting spot for the carrying arm. This way the user does not have to exert their arms as much.



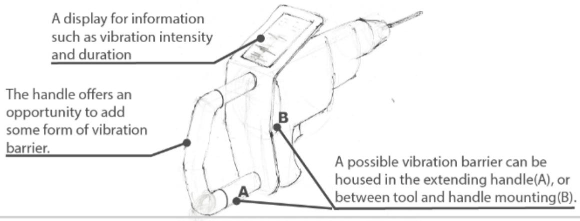
2 User centred, Hand supported

A wrist mounted brace that connects to the power tool



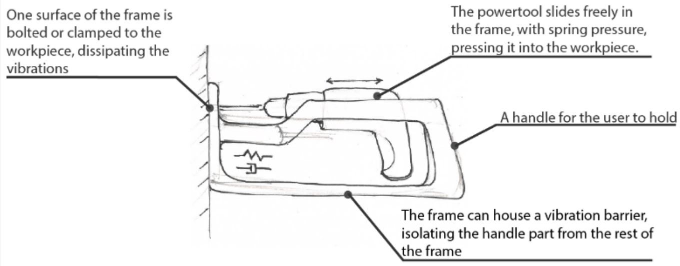
3 Tool centred 2, hand supported

An external handle is added to the power tool. This way the user does not hold the powertool directly.

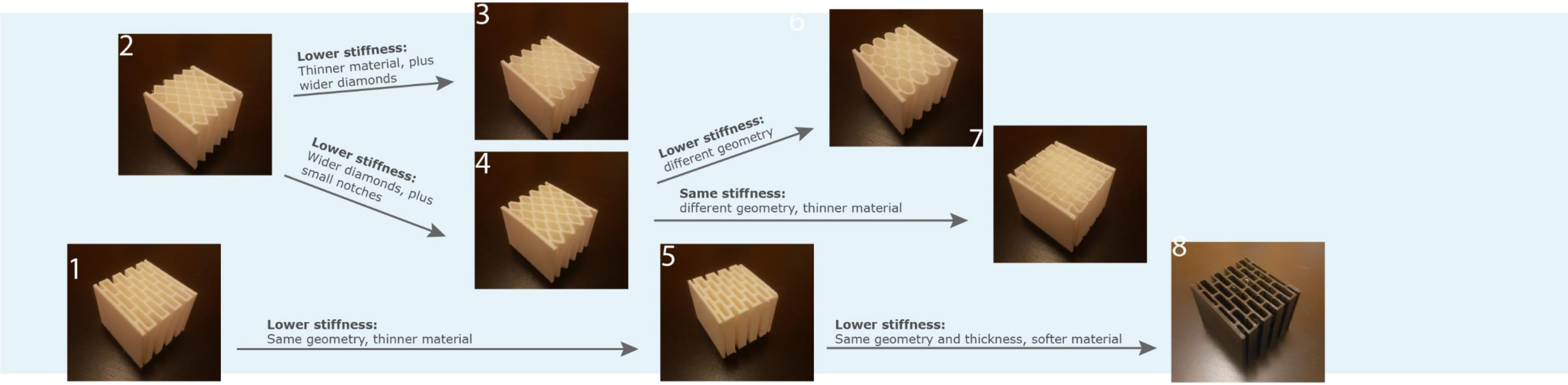


4 Tool centred, workpiece supported

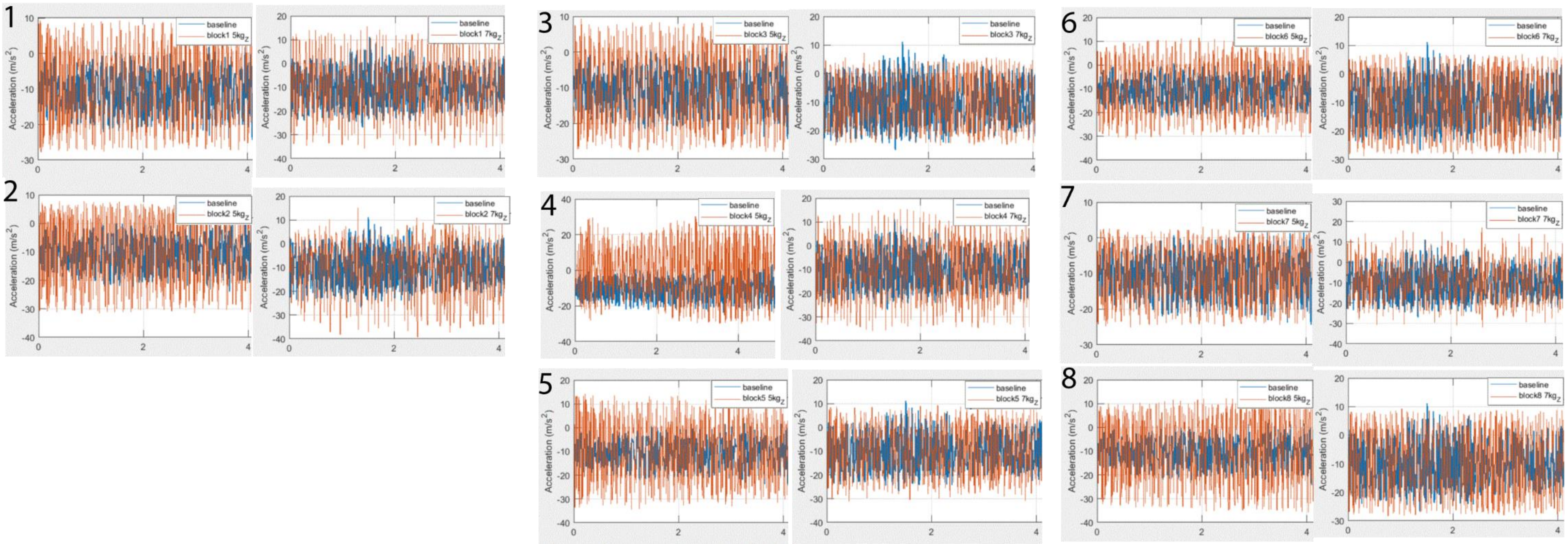
The power tool is suspended in a frame that is affixed to the workpiece(wall).



Appendix 7

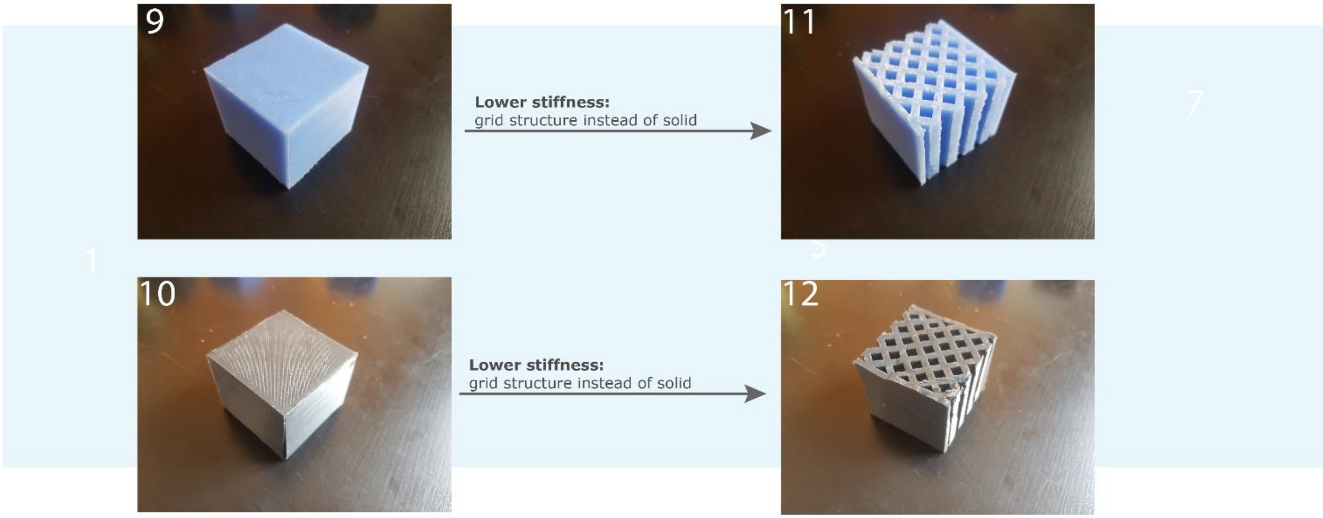


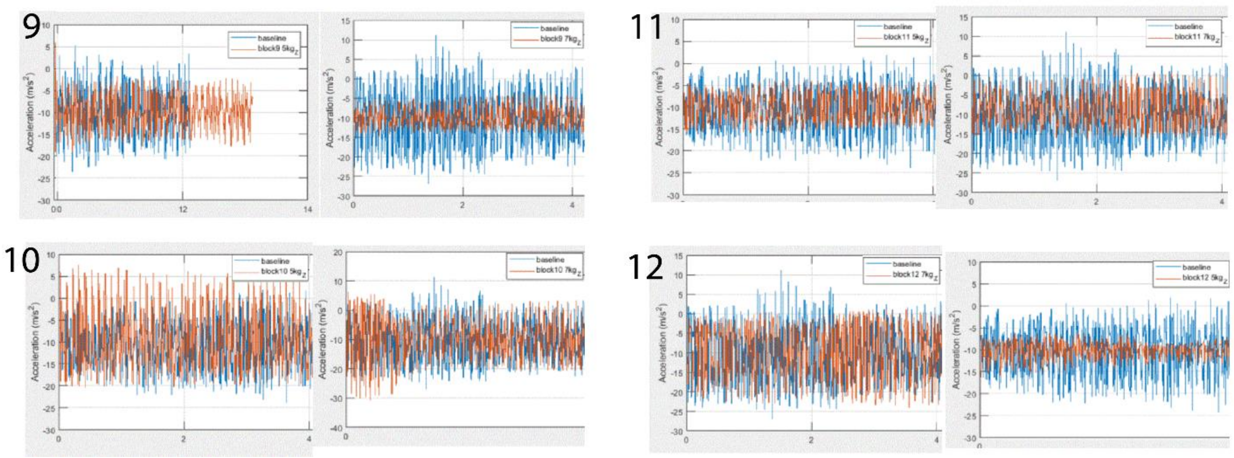
2
Lower stiffness:
Thinner material, plus wider diamonds
3
Lower stiffness:
Wider diamonds, plus small notches
4
Lower stiffness:
different geometry
6
Same stiffness:
different geometry, thinner material
7
1
Lower stiffness:
Same geometry, thinner material
5
Lower stiffness:
Same geometry and thickness, softer material
8



1
2
3
4
5
6
7
8
Acceleration (m/s²)
baseline

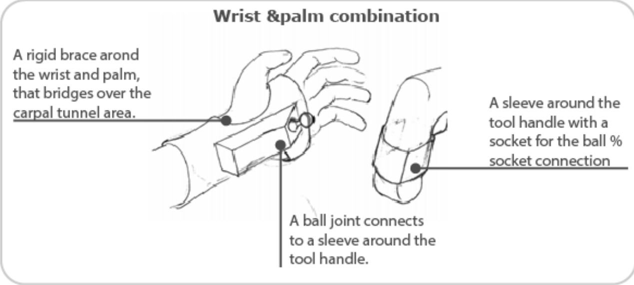
Appendix 8


9
11
Lower stiffness:
grid structure instead of solid
10
12
Lower stiffness:
grid structure instead of solid

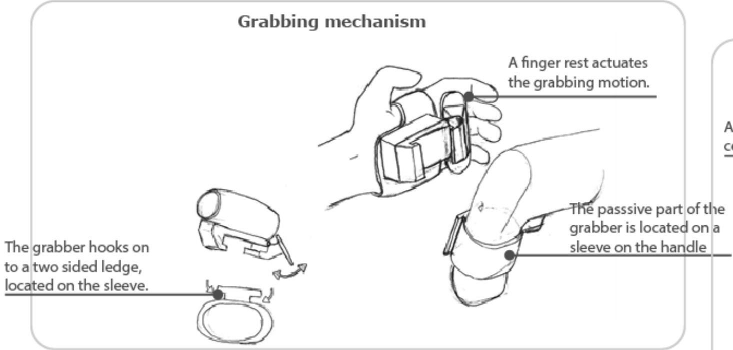

9
10
11
12
baseline
Acceleration (m/s²)

Appendix 9

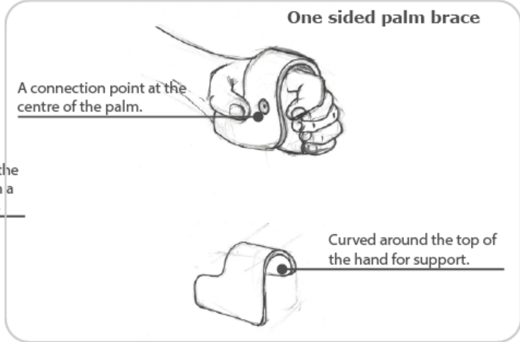
A socket that goes onto the power tool handle.
A palm brace with a black that can slide into the slot on the socket.
Slot connection between hand and handle



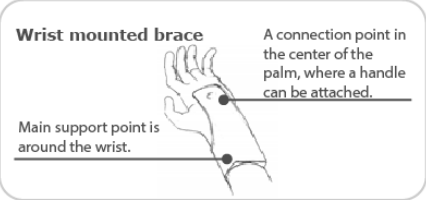
Wrist &palm combination
A rigid brace arond the wrist and palm, that bridges over the carpal tunnel area.
A sleeve around the tool handle with a socket for the ball % socket connection
A ball joint connects to a sleeve around the tool handle.



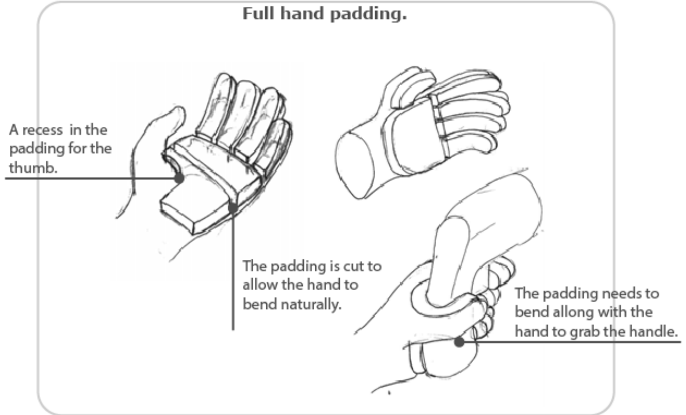
Grabbing mechanism
A finger rest actuates the grabbing motion.
The passsive part of the grabber is located on a sleeve on the handle
The grabber hooks on to a two sided ledge, located on the sleeve.



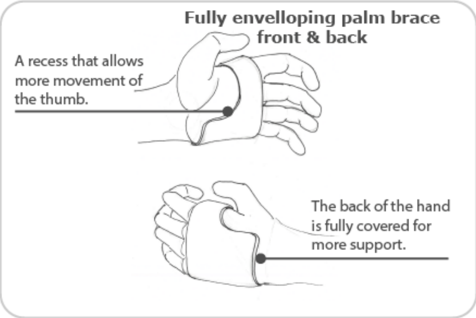
One sided palm brace
A connection point at the centre of the palm.
Curved around the top of the hand for support.



Wrist mounted brace
A connection point in the center of the palm, where a handle can be attached.
Main support point is around the wrist.



Full hand padding.
A recess in the padding for the thumb.
The padding is cut to allow the hand to bend naturally.
The padding needs to bend allong with the hand to grab the handle.



Fully envelloping palm brace front & back
A recess that allows more movement of the thumb.
The back of the hand is fully covered for more support.