TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Mechanical and Industrial Engineering

TOWARDS AN ASSISTIVE TRANSFER AID FOR PEOPLE WITH TETRAPLEGIA: CO-DESIGN AND PROTOTYPING

TETRAPLEEGIAGA INIMESTELE MÕELDUD SIIRDUMISE ABIVAHENDI SUUNAS: KOOSLOOME JA PROTOTÜÜPIMINE

MASTER THESIS

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Tallinn 2026

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Department of Mechanical and Industrial Engineering

THESIS TASK

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Supervisors: Martin Pärn, Senior Researcher - Department of Mechanical and Industrial Engineering;
Daniel Kotsjuba - Estonian Academy of Arts associate professor, head of Social design study programme
Thesis topic:
English: Towards an assistive transfer aid for people with tetraplegia: co-design and prototyping
Eesti: Tetrapleegiaga inimestele mõeldud siirdumise abivahendi suunas: koosloome ja prototüüpimine

Thesis main objectives:

1. Gather knowledge about design requirements that apply to assistive technology in general and about wheelchair transfers activity in the life of people with tetraplegia.
2. Explore design opportunities via co-design activities and prototyping.
3. Propose a design solution for assistive device to facilitate transfers between car seat and wheelchair.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Background research, framework selection	17.02.2025
2.	Design research, interviews, co-design	7.04.2025
3.	Prototyping and testing	15.12.2025
4.	Concept and finalizing the thesis	5.01.2026

Language: English
Deadline for submission of thesis: "5" January 2026

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PREFACE

I want to thank Haapsalu Neuroloogiline Rehabilitatsioonikeskus (HNRK) for allowing me to observe their work with patients and dedicating time of their staff to help out with my research. I’m also grateful to the patients who accepted me observing.

My immense gratitude goes to Siiri Siimenson, HNRK occupational therapist, for her participation in the study, for teaching me about the topic in first hand manner that I would never had expected, but benefitted a lot from, and the positive attitude that calmed and motivated thoughout the process.

Also huge sincere thank you to the person participating in the co-creation workshop for giving me a concrete topic for the thesis and the work contribution during the meetings.

Thank you, to the people who opened their life experiences to me in the interviews.

I also want to thank my advisor Daniel Kotsjuba for the support that calmed my nervousness when I was just approaching the topic area as an outsider and for the invaluable detailed advice in the end of the process.

And finally a thank you to my husband, for the technical support on Latex typesetting that streamlined the writing, proofreading and for bearing with me through my hermit writer days.

LIST OF ABBREVIATIONS

ADL - activity of daily living, regular tasks to take care of one’s body and well-being, like eating and bathing

AT - assistive technology

CAD - computer aided design

DIY - "do it yourself"

FDM - fused deposition modeling, a type of 3D printing technology

HAAT - ”Human Activity Assistive Technology”, a widely used AT adoption model by Cook et al., 2016

HCD - human-centered design

HNRK - Haapsalu Neuroloogiline Rehabilitatsioonikeskus - neurological rehabilitation hospital in Haapsalu

ICF - International Classification of Functioning (WHO Functioning and Disability Reference Group, 2010)

ID - industrial designer

OT - occupational therapist

PD - participatory design

PETG - polyethylene terephthalate glycol-modified, a thermoplastic polymer used in range of applications, including 3D printing

PTFE - polytetrafluoroethylene, polymer also known as Teflon, used for it’s low friction properties

PVC - polyvinyl chloride, a synthetic polymer used in variety of applications including inflatable water sports equipment

PWD - person with disability, PWD-s - people with disabilities

QOL - quality of life

SCI - spinal cord injury

SUP board - stand up paddle board, a water sports equipment

WHO - World Health Organization

CONTENTS

1 INTRODUCTION

Spinal cord injury (SCI) is a disabling health condition that is acquired, often through a trauma event. A large proportion of the SCI-s leave the person paralyzed - motor control (use of muscles) and sensory functions are lost. The extent of body parts affected depends on the location of the injury in the spine. Injuries lower in the spine affect the legs; the higher up the injury is, the more of the torso is affected, and in neck vertebra the arms lose some or all function. When full paralysis affects arms as well as legs, the condition is called *tetraplegia* (also *quadriplegia*), and *paraplegia* if only legs are affected and the functionality of arms and hands remains intact. *Paraparesis* and *tetraparesis* describe injuries where some nerve pathways and some function remains below the injury level.

The most visible result of paraplegia and tetraplegia is its effect on mobility: typically, the person becomes a wheelchair user. In the case of tetraplegia, with the arms and hands affected by paralysis, everyday activities become difficult beyond mobility alone. SCI-s in the highest vertebrae – C1-C3 – leave the person dependent on a ventilator for breathing, C4 disables the arms. C5-T1 is tetraplegia where some use of the arms remains. Besides skeletal muscles, other bodily functions are affected by the nerve pathways damage, in most SCI-s.

Worldwide, SCI-s are more prevalent among men than women. The leading causes of traumatic SCI are falls, traffic accidents, sports accidents and violence; these occur more often in younger age group, from the teens to people in their thirties to forties. Older adults more often suffer from low-impact falls due to osteoporosis, and the numbers are growing with population aging. Non-traumatic SCI-s from tumors and degenerative diseases also occur. The number of people living with SCI-s in the world was estimated at 14.5 million in 2021. In Estonia, the annual incidence rate of traumatic spinal cord injuries is calculated at 39.4 per million. Globally, it is estimated that 15.4 million people live with SCI-s (traumatic and non-traumatic) (WHO, 2024; Kim et al., 2025; Sabre, 2013).

This thesis' research focuses on people with tetraplegia, who have partially lost some function in their arms, but some functionality remains. In Estonian statistics, 28.9% of the traumatic SCI-s have been C5-C8 level injuries (Sabre, 2013). That means, on average, in Estonia about 15 people per year have to learn to live with a paralysis condition that allows only partial use of their arms. Worldwide about half of the SCI population (7.30 million) have neck-level injuries, (C1-C8 without further specification) (Kim et al., 2025).

For people with tetraplegia where some arm function remains, significant gains of independence are possible in the presence of suitable assistive technologies (AT-s). One challenging everyday task is moving between a wheelchair and other seating surfaces (for example a bed or a car seat), because without the use of triceps and torso muscles, it is very difficult to transfer (go from one seating surface to another). The transfers are difficult even when there is a caretaker present, since moving an adult person's body, even a short distance, is significant physical work. There is a wide variety of transfer AT-s already invented, yet they seem to fall into two categories: large hoists that can't be taken out of home/hospital, or very simple, relatively compact transfer boards that work well in some conditions, for both independent transfers and with another person assisting, but fail when the seat heights don’t match.

Though I started the thesis process with a personal interest in facilitating independence where there might be a bottleneck, a slightly modified problem emerged during interviews. Specifically, transferring into a car and out again might not be a task that many people with tetraplegia would choose to do completely alone at this time, but car transfers are among the most difficult and sometimes pose a barrier even in the presence of one caregiver, especially the transfer out from a sedan car, into a wheelchair.

This problem seems overly narrow at first glance, but several authors recommend ”design for one” approach as the center for frameworks when designing AT (De Couvreur et al., 2011a; Aflatoony et al., 2023). Solving a very contextual problem for one person can result in significantly better results than attempting to ”average” a user group. Looking for other user groups and use cases can be done after the initial design has started to take shape.

In human-centered design (HCD) / user-centered design terms getting out of a car is not an *activity*, but clearly just a *task*, and a very low-level one too. In HCD, the designer is expected to design for activities, not tasks *usually* (Norman, 2013). Yet the low-level tasks pose barriers to people with disabilities (PWD-s). In general, barriers can be remedied from two sides: first infrastructure and products can be built in a way that they don’t create barriers (universal design, design for all, inclusive design approach) and secondly AT devices can provide an alternative mode to accomplish the task result. This thesis tries to offer an AT remedy for the individual in the world where car design is not sufficiently accessible yet.

Because the subject of the design attempt is an atypically narrow task and because we need to avoid repeating a historical pattern of taking the agency away from people with disabilities, the design process was done without the initial divergence phase (as in the double diamond model). That is, without asking if we are solving the right problem (Norman, 2013). The understanding of the context was developed via desk research, observation and interviews, but I never had the audacity to suggest that the problem should be solved ”elsewhere” than where the problem owner in the co-design was pointing to. The client was trusted as the expert on the nature of their problem.

The absence of a questioning phase for the problem statement puts this thesis a little bit out from the design curriculum and moves it a step closer to engineering. This is intentional, for the sake of my personal goals. As a result, engineering is more heavily involved in the form of the extensive physical prototyping, compared to a typical design thesis. The designerly methods (e.g. mapping, semi-structured interviews, co-creation workshop) are used in order to understand the broad context, then, with the detour to prototype engineering, users’ test results are acquired and a new concept proposed based on new insights from the testing.

The aim of this thesis is to explore challenges people with tetraplegia face in wheelchair transfers, through a co-design and prototyping process, in order to inform the development of a transfer aid.

1. What are the key physical, social and personal factors shaping the experience of wheelchair transfer for people with C5-C7 level tetraplegia?

2. What priorities and requirements from the perspectives of people with tetraplegia and caregivers emerge from co-design activities within a design-for-one context?
3. What does iterative prototyping contribute to the understanding, that the verbal and visual communication alone do not reveal?

The thesis consists of following chapters:

2. Background study chapter has three subsections: First is a brief overview of SCI-related topics - medical, psychological and others. Second, a history perspective on disability and design touch points - the agency of the PWD-s, legislative milestones regarding disability rights and relevant design philosophies. Third, a brief section on the 'AT abandonment problem', a topic that appears in nearly all studies on AT.
3. Theoretical frameworks chapter introduces HAAT (a framework used in AT research – not design-specific) and four different suggested AT design frameworks from which elements were selected for this thesis project.
4. A methodology chapter, which gives a quick overview of the practical side of the research, development and testing process.
5. A design research chapter, composed of three parts. First, an overview of the conducted interviews with people living with tetraplegia. Second, the activity of transferring from one seat to another is described from the (bio)mechanical point of view. Third, an overview of existing transfer AT solutions.
6. Concept exploration chapter follows the remaining process. It describes the co-design workshop held with one user and an occupational therapist – its process and results. Second, a brief overview of built prototypes. And finally, the prototypes testing results are laid out.
7. Design concept proposal chapter describes a product that addresses a problem that was identified more precisely during the testing of the prototypes.

Appendix 1 is the interview questionnaire. Appendices 2, 3 and 4 contain the consent forms given to interview participants, co-creation workshop participants and testing participants respectively. Appendix 5 is there to make it more transparent why one of the two prototypes was built different than the original concept saw it. Appendixes 6 and 7 give more detailed description of the build of the two prototypes, going briefly over materials, methods and important parameters.

Keywords: Design for assistive technologies, wheelchair transfers, co-design, master thesis.

2 BACKGROUND STUDY

2.1 Spinal cord injury

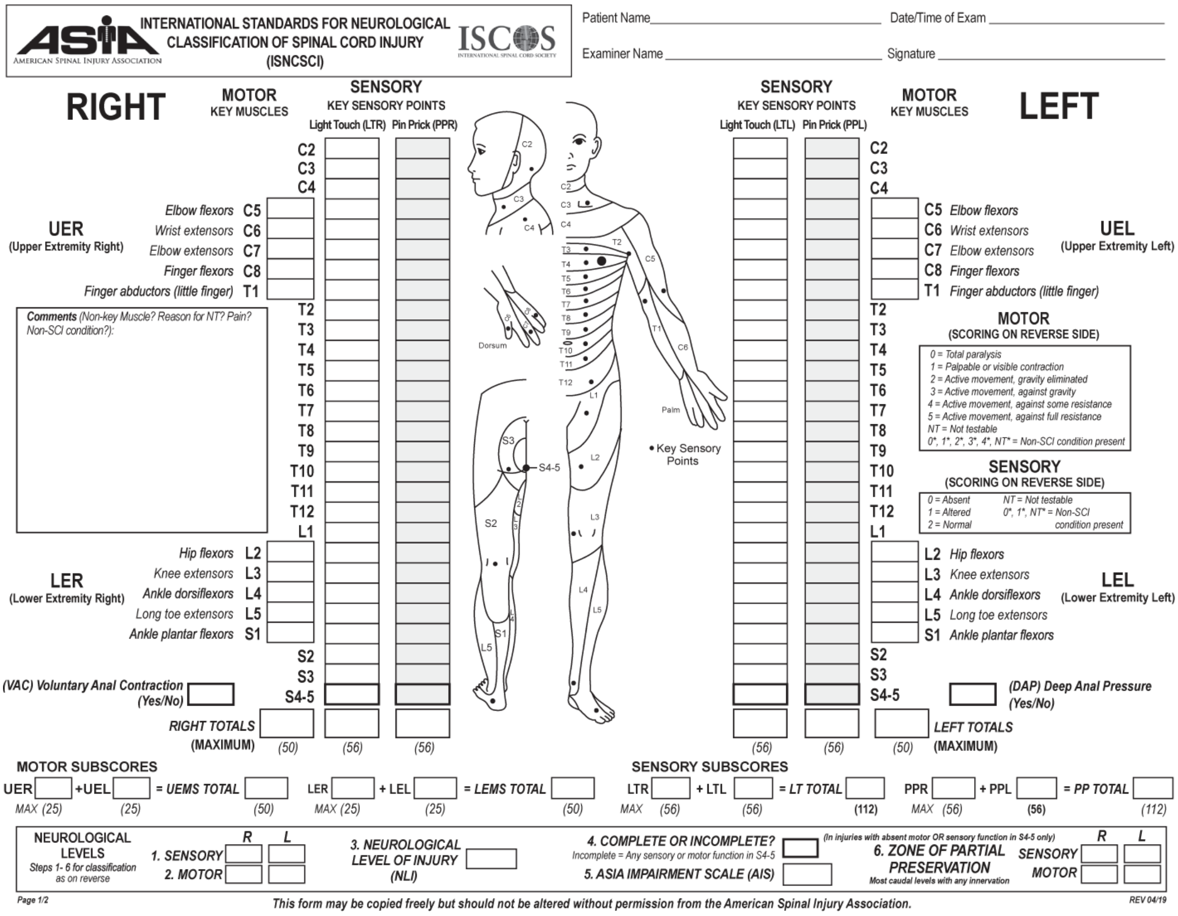
2.1.1 What is spinal cord injury?

The spinal cord is a bundle of nerves that runs down from the brain, through the vertebrae - stacked hollow individual bones - of the spine. Separate strands carry nerve signals down from the brain to activate muscles (descending or motor nerve pathway) and up to the brain as sensory input (ascending or sensory nerve pathway). The spinal column consists of 33 bones separated by cartilage disks and 31 pairs (for each side of the body) of nerves. The top 7 vertebrae are called the cervical spine, and the 8 pairs of nerves exiting from there serve the muscles and skin sensory nerves in the arms. The following 12 are part of the thoracic spine, and the 12 pairs of nerves serve mainly the torso. 5 lumbar vertebrae and pairs of nerves serve the upper and front (anterior) sections of the legs. The sacral region of the spine also has 5 vertebrae and 5 pairs of nerves and serves the back (posterior) section of the legs, the bladder and the bowel. And finally, the coccygeal section has 4 vertebrae and 1 pair of nerves (Roberts et al., 2016)

The majority of spinal cord injuries (SCI) happen as a result of external forces - traumatic SCI-s - caused by falls, traffic accidents or violence. In traumatic SCI-s a crushing force destroys the nerve cells and tracts. Non-traumatic causes are tumours, degenerative conditions, infections, toxins or birth defects. (WHO, 2024)

The injuries are described with "level" that denotes the vertebra just above the injury location where the function has remained intact. It is marked with a letter as the region of the spine (C - cervical, T - thoracic, L - lumbar, S - sacral) and the number of vertebrae counted down from the top of that section. For example, C7 is the seventh cervical vertebra, T1 is the first thoracic vertebra, and so on. Injuries can be either complete - all nerve pathways are damaged and non-functioning at the level of injury and below - or incomplete, in which case some nerve signals, either sensory or motor, pass through. Paralysis and loss of sensation affect the areas of the body served by the nerves that exit the spine below the injured area. In case of complete injury, both motor and sensory function are fully lost, while an incomplete injury means that one or the other has at least partially remained. (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

The international standard for neurological classification of SCI is a set of procedures doctors use to assess the muscle control and sensations to give a diagnosis that expresses the level of injury and supplements it with a letter that grades the completeness of the injury - American Spinal Injury Association Impairment Scale (AIS) (see figure 2.1). A complete injury is letter A. B means some sensory, but no motor function below the level of injury, C means motor function is present but weak, and D means motor function is present in at least half of the muscles. And E means that both sensory and motor function tests are normal, yet the person has abnormal reflexes or other neurological phenomena. But it should not be assumed that a complete injury on the same level in different people will result in an identical physical state - there is a lot of individual variability. (Roberts et al., 2016; Rupp et al., 2021)



ASIA AMERICAN SPINAL INJURY ASSOCIATION
INTERNATIONAL STANDARDS FOR NEUROLOGICAL CLASSIFICATION OF SPINAL CORD INJURY (ISNCSCI)
ISCOS INTERNATIONAL SPINAL CORD SOCIETY

Patient Name__________ Date/Time of Exam __________
Examiner Name __________ Signature __________

RIGHT MOTOR KEY MUSCLES | SENSORY KEY SENSORY POINTS Light Touch (LTR) Pin Prick (PPR)

SENSORY KEY SENSORY POINTS Light Touch (LTL) Pin Prick (PPL) | MOTOR KEY MUSCLES **LEFT**

C2
C3
C4

UER (Upper Extremity Right)
Elbow flexors C5
Wrist extensors C6
Elbow extensors C7
Finger flexors C8
Finger abductors (little finger) T1

UEL (Upper Extremity Left)
C5 *Elbow flexors*
C6 *Wrist extensors*
C7 *Elbow extensors*
C8 *Finger flexors*
T1 *Finger abductors (little finger)*

Comments *(Non-key Muscle? Reason for NT? Pain? Non-SCI condition?):*

T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
T12
L1

MOTOR (SCORING ON REVERSE SIDE)
0 = Total paralysis
1 = Palpable or visible contraction
2 = Active movement, gravity eliminated
3 = Active movement, against gravity
4 = Active movement, against some resistance
5 = Active movement, against full resistance
NT = Not testable
0, 1*, 2*, 3*, 4*, NT* = Non-SCI condition present*

SENSORY (SCORING ON REVERSE SIDE)
0 = Absent *NT = Not testable*
1 = Altered *0*, 1*, NT* = Non-SCI condition present*
2 = Normal

LER (Lower Extremity Right)
Hip flexors L2
Knee extensors L3
Ankle dorsiflexors L4
Long toe extensors L5
Ankle plantar flexors S1

LEL (Lower Extremity Left)
L2 *Hip flexors*
L3 *Knee extensors*
L4 *Ankle dorsiflexors*
L5 *Long toe extensors*
S1 *Ankle plantar flexors*

S2
S3
S4-5

(VAC) Voluntary Anal Contraction (Yes/No) ☐
☐ *(DAP) Deep Anal Pressure (Yes/No)*

RIGHT TOTALS (MAXIMUM) *(50)* *(56)* *(56)*
(56) *(56)* *(50)* *LEFT TOTALS* (MAXIMUM)

MOTOR SUBSCORES
UER ☐ +UEL ☐ = *UEMS TOTAL* ☐ LER ☐ + LEL ☐ = *LEMS TOTAL* ☐
MAX (25) *(25)* *(50)* *MAX (25)* *(25)* *(50)*

SENSORY SUBSCORES
LTR ☐ + LTL ☐ = *LT TOTAL* ☐ PPR ☐ + PPL ☐ = *PP TOTAL* ☐
MAX *(56)* *(56)* **(112)** *MAX (56)* **(56)** *(112)*

NEUROLOGICAL LEVELS
Steps 1- 6 for classification as on reverse
R *L*
1. SENSORY ☐ ☐
2. MOTOR ☐ ☐
3. NEUROLOGICAL LEVEL OF INJURY (NLI) ☐
4. COMPLETE OR INCOMPLETE? ☐
Incomplete = Any sensory or motor function in S4-5
5. ASIA IMPAIRMENT SCALE (AIS) ☐
(In injuries with absent motor OR sensory function in S4-5 only)
6. ZONE OF PARTIAL PRESERVATION
Most caudal levels with any innervation
R *L*
SENSORY ☐ ☐
MOTOR ☐ ☐

Page 1/2
This form may be copied freely but should not be altered without permission from the American Spinal Injury Association.
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Figure 2.1: Worksheet for diagnosing the level and completeness of SCI. (Rupp et al., 2021)

The booklet Queen Elizabeth National Spinal Injuries Unit, 2015 lists 6 different types of incomplete injuries. Paralysis, as well as sensations of hot, cold, and pain are caused by injuries to the front (anterior) part of the spinal cord, while light touch, vibration and joint position sensing are located in the back (posterior) of the spinal cord. If only one side of the spinal cord is damaged, the same side of the body becomes paralyzed, and the sense of light touch and joint position are lost there, while feelings of hot and cold, sharp or blunt, disappear on the opposite side of the body instead, because they travel on the side of the spinal cord that is opposite to the source of sensation.

The spinal cord - part of the central nervous system - runs in the spine down to the waist area. Lower down, it divides into a bundle of nerves called the *cauda equina*, which is already part of the peripheral nervous system. If the injury affects the *cauda equina*, the muscles in the legs and the ones controlling the bladder and rectum become flaccid. Different from the flaccid paralysis is *spastic* paralysis - in case of the injuries higher up, in the central nervous system, nerve signals originating from the spinal cord itself below the injury, travel to the muscles and cause muscles to contract, expressed as involuntary movements or muscle tension. (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

If a complete injury causes paralysis that affects the arms as well as legs and torso, the condition is called tetraplegia (also quadriplegia). Paraplegia is paralysis in the legs and lower torso, but normal functioning in arms and hands. Tetraplegia is caused by injuries at the level of the cervical vertebrae and down to T1. Tetraparesis and paraparesis refer to respective conditions of incomplete injuries. (Bergmann et al., 2018)

2.1.2 Incidence rate of spinal cord injury

WHO estimates that approximately 15.4 million people were living with SCI in 2021. This number includes traumatic and non-traumatic SCI-s (WHO, 2024). Another recenet study put the number at 14.5 million and distinguished 7.30 million as neck-level and 7.22 million as below-neck-level injuries (Kim et al., 2025).

The incidence and patterns of the causes differ between countries. The methodologies to determine the numbers vary between studies in different countries; many have excluded the patients who have died at the scene of the accident and in the acute phase of the injury. In Europe, the highest reported incidence has been in Portugal at 57.8 per million of population, the lowest being in Italy at 2.3 per million. In Estonia, the incidence rate of traumatic SCI-s was calculated as 39.4 per million based on the decade 1997-2007. Incidence rate of non-traumatic SCI-s was not covered in this Estonian study. (Sabre, 2013)

Between world regions the causes differ. In high income countries sports, road-traffic and self harm are prevalent among young adults, while in middle income countries threre are more occupational exposure related accidents, and finally a distinct pattern arises in countries that have seen long term armed confict. High income countries are projected to see decrease in absolute numbers by 2050 due to population decrease and prevention strategies. At the same time East-Asia will see significant growth in SCI numbers due to population aging, and low and middle income regions will have an increase due to population growth. (Kim et al., 2025)

Incidence rate is much higher among men than women in the whole world and locally. In Estonia, the rates were 72.0 per million for ment and 11.5 per million for women, respectively. In Estonian statistics, the age group 20-29 was most frequently affected, and the leading causes in this age group were traffic accidents and sports. In older age groups, the leading cause was falls, while sports as the cause declined steeply, and traffic accidents also declined towards the older age groups. The mean age of the people suffering the trauma in the research period was 39 (standard deviation 17.2) and median 36. Among sports injuries, diving accounted for 91.4%. 15.2% of the traumas were work-related. 23.9% of the patients got a diagnosis with AIS D grade (motor function intact in at least 50% of the muscles below the injury level). Grade A, B and C injuries, divided into injury level groups, were as follows: 9.9% C1-C4, 28.9% C5-C8, 26.7% T1-S5. Most frequent levels were C5, C6 and L1.(Sabre, 2013)

Surprisingly, low impact fall as a cause, that affects the older population due to osteoporosis and impaired balance, is more likely to lead to neck-level injury. Traffic accidents and violence have a higher proportion of below-neck level injuries as outcome. (Kim et al., 2025)

2.1.3 Physiological consequences of spinal cord injury

Ambulation. The ability to walk is affected in the majority of SCI cases. Incomplete injuries may permit walking on crutches, but complete injuries in all cervical and thoracic levels cause paralysis in all muscles of the lower limbs. Lumbar level injuries paralyze some leg muscles. Therefore, relying on a wheelchair for getting around is very common after an SCI. Injuries in the highest cervical levels (C4 and up) make the person fully dependent on others or on high-tech mobility solutions. (Roberts et al., 2016)

Paralysis in the arms. Injuries above T1 affect muscle control in the arms (see table 2.1).

Table 2.1: Levels of SCI injury and muscles affected. (Roberts et al., 2016)

Level of injury	Muscles affected by injury
C5	elbow flexors (biceps)
C6	wrist extensors
C7	elbow extensors (triceps)
C8	finger flexors
T1	finger abductors

Respiratory system. Breathing is a movement accomplished by several different muscles working together. The most important of them, the diaphragm, is controlled by nerves in the C3-C5 levels. People suffering injury C1-C3 will need a ventilator to breathe. C4-C8 will have their breathing affected, but can breathe on their own. The external intercostal (between ribs) muscles normally participate in breathing, making the rib cage lift. If T1 to T10 injury disables them, the breaths will be smaller, which can make the person feel tired. Lack of external intercostals and inability to breathe in deeply also make it difficult to remove the mucus from the lungs that is produced to protect from dust and pathogens. Internal intercostals (T1-T10) normally help in breathing out. Abdominal muscles (T6-T12) contract when coughing and support the diaphragm in its best working position. When internal intercostals and abdominals are affected by the paralysis, it becomes impossible to cough effectively to remove mucus; excess mucus makes the lungs susceptible to infections. Coughing assisted by a caretaker is one management technique for this issue. (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

Bladder and bowel. In spastic paralysis, the bladder is not under conscious control of the person any more, and urination may occur unwillingly when the signal of a full bladder is received by the spinal cord. Flaccid paralysis causes continuous incontinence. An indwelling catheter or intermittent cathetherization (in case of paraplegia, sufficient manual dexterity), or a few other options are available for bladder management. The bowel function will be altered after SCI as well, depending on the injury level. Lower than

T12 level injury causes slowing down of the peristalsis, leading to constipation, while at the same time the anal sphincter remains flaccid and causes "accidents". Higher-level injuries allow the gut to digest relatively normally, but because of a lack of sensory signal to the brain, the bowel may again empty at unexpected moments. In both cases, the goal is to achieve predictability, and each person has to create a bowel routine for themselves where they use techniques to empty the bowel at will at regular times and know how to support the regularity with diet. (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

Musculoskeletal system and spasticity. When the muscles are not used for daily activities, deconditioning (loss of muscle mass) and muscle atrophy happen. It can be seen as partially beneficial as the lighter paralyzed limbs are easier to manage, yet it comes with downsides, too. Fewer muscles mean less demand on the cardiovascular system, and it can suffer deconditioning too as a result. Muscles pulling on the bones maintain bone density, and when these forces disappear, osteoporosis is a common consequence. Areas where bones are not padded with muscles are more likely to get skin problems. Spasticity is the occurrence of muscle spasms that is caused by signals coming from the spinal cord below the injury level, and the presence of mild spasticity reduces the muscle loss to some extent. To counteract the muscle atrophy, some exercise can be done with an electrical stimulation (FES) device that makes the muscles in the paralyzed areas contract. (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

When spasticity keeps a joint in the same position constantly, and the joint's range of motion is not used, the joint may become stiff to the level of permanent contraction. Stretching and assisted range of motion (ROM) exercises are recommended to prevent it. Standing upright regularly with the help of assistive devices - a standing frame or a tilt table - is also recommended. (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

Sudden and stronger spasms can have negative effects if they interfere with activities. Stretching, vertical position and even medication are used to suppress them. When the frequency of spasms increases compared to what the person experiences usually, it might indicate some kind of pain sensation below the injury level, for example, bladder stones (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

Regulating body temperature. The functions of sweating in response to a too-hot environment and response of reducing blood flow to the skin as well as raising goosebumps in response of cold stop working after SCI in the areas below the injury level. Therefore tetraplegics need to pay attention to potential temperature discrepancies and take measures to avoid hyper- and hypothermia. (Queen Elizabeth National Spinal Injuries Unit, 2015)

Skin. The situation where signals of hot, cold, touch, and pain from nerves in the skin do not make it to the brain creates dangers of causing injury to the skin without realizing it. The likelihood of developing pressure sores and friction wounds is elevated even more by the muscle atrophy that makes bones protrude and by the need to be sitting in a wheelchair for long hours, as getting up is not an option. Pressure sores are a risk that people with SCI have to keep in mind constantly and take measures to relieve pressure at regular intervals in a wheelchair and during bed rest. Also, daily skin checks are advised. (Queen Elizabeth National Spinal Injuries Unit, 2015; Bergmann et al., 2018)

Pain. Neuropathic pain and chronic pain are prevalent and negatively affect the quality of life for people with SCI. (Bergmann et al., 2018)

Autonomic dysreflexia. Autonomic dysreflexia is a sudden onset condition that raises the blood pressure to extreme heights and poses even a risk of death. The condition can affect people with injuries at T6 or higher and is more likely the higher the injury level is. An episode of autonomic dysreflexia can be triggered by an overfilled bladder, urinary tract infection, kidney or bladder stones, constipation, pressure sores, or other pains or discomforts in the lower body. An episode of autonomic dysreflexia has to be addressed quickly by resolving the triggering cause and lowering the blood pressure to a safe level. (Bergmann et al., 2018)

2.1.4 Rehabilitation process after SCI, role of an occupational therapist

The rehabilitation process after SCI begins in an acute care hospital and continues in a rehabilitation hospital. A team of medical and non-medical specialists are working with the patient with SCI: a doctor, physiotherapist, occupational therapist, psychologist, social worker, nurse, caretaker, speech therapist (if needed), and peer counsellor. (Bergmann et al., 2018; Physiopedia, n.d.)

In Estonia, people with SCI-s, after stabilizing treatment in a general hospital, are transferred to a rehabilitation hospital (usually HNRK) or a rehabilitation department. They spend several hours a day in various physical and occupational therapies. After release from the hospital and returning to community life, chronic SCI patients return to HNRK on a regular basis, usually once or twice a year, for several consecutive days filled with physiotherapy and occupational therapy (Bergmann et al., 2018 and personal communication, 3.03.2025).

An occupational therapist (OT) is a specialist whose task is to enhance patients' ability to execute activities of daily living (ADL-s) and train fine motor skills. OT-s teach compensatory strategies and provide or recommend AT-s. The goal is to help the patient adapt to their environment and achieve social inclusion. For example, the OT instructs on eating, dressing, and washing if dexterity is limited, as well as on the use of a wheelchair and techniques to transfer into and out of the wheelchair (independently where achievable or with help). (Bergmann et al., 2018; Physiopedia, n.d.)

In wheelchair transfers, one recurring topic is fear of falling. A person with tetraplegia cannot use their abdominal and torso muscles and can have difficulty knowing how far they can lean forward in a seated position and trust their arm strength to push themselves up again. OT encourages the patient to learn their actual limits (and also to train the available muscles to extend those limits) and to use the full range they can manage, along with inertia and other tips and tricks, to eventually learn to transfer independently. Everyone's journey of recovery and learning is different, and OT supports it in a flexible manner, according to the person's own priorities (personal communication and observation in HNRK, 3.03.2025).

2.1.5 Quality of life after SCI and autonomy

A sense of loss is likely a common occurrence after SCI, because of the sudden need to rely on carers for everyday tasks such as hygiene procedures that people are used to doing in privacy, loss of spontaneity, such as the inability to leave home at one's own accord, and difficulties engaging in activities that used to define one's self (Dickson et al., 2008). While the need to rely on a wheelchair for mobility can be accepted relatively better, stigmatization that might occur from that condition has a significant correlation with lower quality of life (QOL) and depression (Dickson et al., 2008; Gurung et al., 2023). Among people who have suffered incomplete SCI-s, QOL was observed to be best for people who had become independent wheelchair users compared to those who managed to regain some ambulation but had to rely on others' help to do so, and wheelchair users needing external help (Krause et al., 2009).

Strategies that enable autonomy for people with SCI have been researched in a small study van de Ven et al., 2008, that recruited C6–C7 tetraplegics from a wheelchair rugby club. The strategies were analyzed and matched to a four-dimensional concept of autonomy. There were several strategies under each dimension. The four dimensions themselves, derived from prior research, were the following:

1. Daily life (executional) autonomy – getting things done without the help of others;
2. Self-determination (decisional autonomy);
3. Participation, having social roles and relationships;
4. Identification – feeling comfortable in one's way of living. (van de Ven et al., 2008)

Balancing and compromises between executional autonomy and participation were experienced as usual part of life (van de Ven et al., 2008).

A systematic literature review van Dam et al., 2024 looked for distinct areas of independence that people with various disabilities could gain from assisted living technology (such as power wheelchairs, computer access assistive technologies, and environmental control systems) and managed to determine six. Figure 2.2 lists them and shows my attempt to relate them to the dimensions of autonomy described by van de Ven et al., 2008.

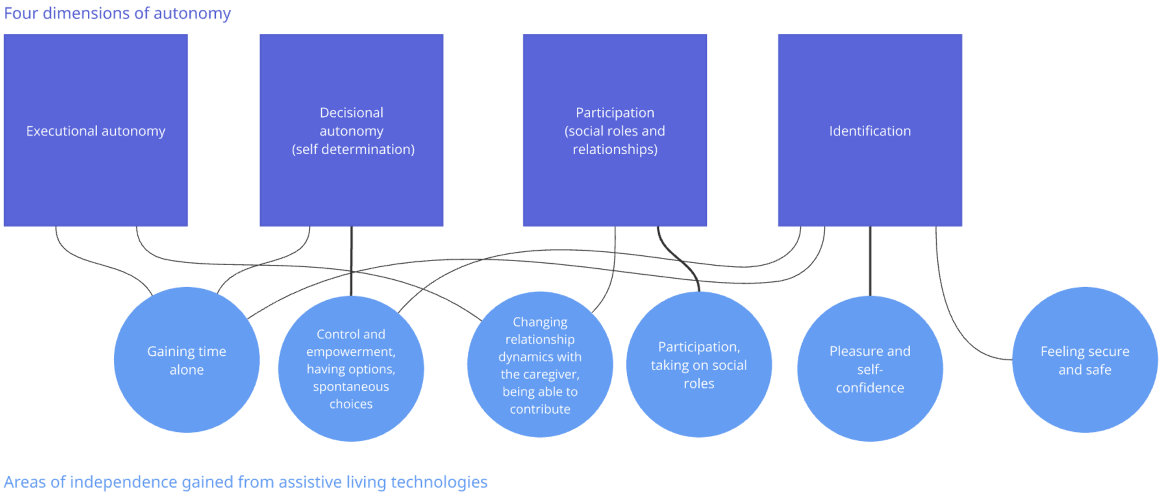


Figure 2.2: Comparison of four dimensions of autonomy by van de Ven et al., 2008 and areas of independence by van Dam et al., 2024

2.2 Disability and design history

2.2.1 Pre-industrial era

By several authors' opinions, the pre-industrial era was a sweet time when people with disabilities were in charge of their own needs and had agency in the design done for them. Disability-related objects were crafted with equal care for their aesthetic appearance as any other possessions, and they could even serve as a canvas to show off wealth and status. (Kille-Speckter et al., 2022; Belolan, 2020; Pullin, 2009)

The records and material artifacts that the authors have examined are not plentiful, and most of them belonged to wealthy members of society. A success story — Andrew Gawley, who invented practical prosthetic arms after double amputation — that Kille-Speckter et al., 2022 use to illustrate the pre-industrial state of things actually dates to the 1890s. Their point, however, is that there was an era when most things were produced in the context of customers having direct contact with craftspeople, without a corporate designer and their preconceptions in between.

2.2.2 Late 19th, early 20th century. Medical model of disability

The industrial revolution brought specialization and standardization in production practices. Simultaneously, the narrative about disability became one in which the "non-standard" bodies of people with disabilities were seen as needing either a medical cure or fixing with assistive devices — this is called the medical model of disability. The industry was ready to offer these fixes. With the medical model, images of "overcoming" disability and working despite it were idealized. (Kille-Speckter et al., 2022; Virdi, 2020)

A large cohort of young men injured in World War I were faced with exactly that societal expectation to regain productivity through employment. Some tools, such as arm prostheses, were offered by governments; at the same time, these products may not have been the best the technology could offer, but rather compromises between features and cost (Virdi, 2020).

During World War II, effective treatments were developed for spinal cord injuries, and veterans were the first to have a significant chance of survival beyond a few months' prognosis. They had to return to civilian life and find employment. A development in wheelchair design happened at the same time: what had been a heavy tool for hospital personnel to transport a passive patient became something with which a person themselves, if in possession of sufficient upper-body strength, could propel themselves around alone — a facilitator of independence. When it came to employment, veterans sought out workplaces where accessibility was pre-existing accidentally or where volunteers were ready to make up for the lack of it — there was not yet a policy about infrastructure accessibility. (Tremblay, 1996)

In the 1950s, the medical model of disability may have been visually reinforced by the fact that in previous decades tubular steel wheelchairs had resembled contemporary furniture, but in the 1950s bent plywood took over homes and offices, while hospital equipment and wheelchairs remained similar to each other. A few decades later, with the cohort of Vietnam War veterans, wheelchairs saw the introduction of military and space materials. Over time, the stereotype of a wheelchair user changed from an old lady to a young man. (Pullin, 2009)

2.2.3 Second half of the 20th century. Social model of disability

The disability rights movement has its roots in the 1960s alongside other minority rights movements and developed further through the following couple of decades. It opposed the medical model, which saw the issue as being solely attached to the disabled person and needing a cure or fix, and proposed a new model. The social model of disability claims that the barriers set by societal systems outweigh the direct consequences of the physical limitations a person may have. Therefore, action has to be taken to change society and attitudes. (Kille-Speckter et al., 2022)

Even though the social model of disability had been conceived, in practice the medical model remained dominant in healthcare and policy for the following decades.

From here on, design for disability has two facets: design of assistive devices (sometimes called rehabilitation engineering) and design for accessible infrastructure that is directed not at a single user with a disability, but at all potential users of buildings and products.

Schools of thought, or ideologies, on accessible infrastructure varied between countries. In the United States, though leading the initiative in the 1960s, the assumption was that infrastructure had to facilitate total independence. Differentiation between people was so frowned upon that labeling a facility as wheelchair accessible was prohibited. (Guffey, 2020)

In the United Kingdom, Selwyn Goldsmith was tasked with creating building accessibility standards. After initially taking examples from the US, he proceeded to do local research, which led to a very different picture. Goldsmith's second edition of *Designing for the Disabled* from 1967 set the direction for the following decades. In his research, Goldsmith saw that independence was very rare among wheelchair users when realistic age distribution was considered. People needed care. One place where this care is reflected in the UK is in special unisex wheelchair-accessible public toilets, clearly labelled as such, because many people go out only with a family member caretaker of the opposite sex, and single-sex toilets, even with enough maneuvering space and rails, are of no use for them. (Guffey, 2020)

2.2.4 End of the 20th and beginning of the 21st century. Biopsychosocial model of disability

The disability rights movement gradually changed mindsets and led to political change. One major milestone was the Americans with Disabilities Act (ADA) in 1990, which prohibited discrimination on the basis of disability in employment, public services, transportation, telecommunications, and public accommodations. (Kille-Speckter et al., 2022)

The WHO published its new International Classification of Functioning and Health (ICF) in 2001 — a scientific tool for member states to improve their health policies. This marked a step away from the medical model that saw only a direct link between impairment — divergence from normal body structure or functioning — and disability — limitation with regard to an activity. The model used in the ICF is called the biopsychosocial model, and it sees disability in a wider framework of body functions, body structure, activities, participation, and environmental and personal context (see Figure 2.3). One of the intentions was also to distance from binary categorizations of people as disabled or non-disabled and to emphasize the contextual nature of disability, recognizing that over a lifespan everyone is likely to experience some disability. (WHO Functioning and Disability Reference Group, 2010; Kille-Speckter et al., 2022)

The United Nations Convention on the Rights of Persons with Disabilities (CRPD) was adopted in 2006 — a legally binding obligation for states to take action in removing environmental, social, and attitudinal barriers to enforce the human rights of people with disabilities (European Commission, n.d.). Estonia ratified it in 2012 (Sotsiaalministeerium, 2021).

In the digital age, barriers have to be addressed in the ICT field as well. One impactful case is the World Wide Web Consortium (W3C) Web Content Accessibility Guidelines (WCAG) standard, which aims to ensure content is perceivable, operable, understandable, and robust — accessible by everyone, regardless of sensory or physical limitations. (W3C, n.d.)

2.2.5 Relevant design philosophies and approaches

Since the 1950s, accessibility has been a topic that design is supposed to address. In the US, the first standard, "Making Buildings Accessible by the Physically Handicapped," was published in 1961, and at the same time domestic products and public transport developed toward enabling more diverse users. (Persson et al., 2015)

While the roots of accessibility thinking can be traced to enabling community life for war veterans and education for younger people with disabilities (Hendren, 2020), in the 1980s–1990s a concern arose over population ageing (Clarkson et al., 2015).

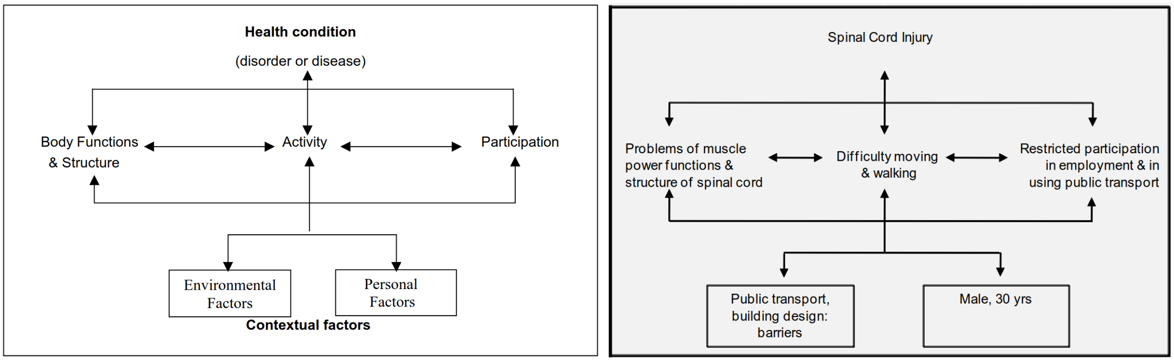


Figure 2.3: Representation of the biopsychosocial model of disability (WHO, 2002) and an example of ICF use with an individual (WHO Functioning and Disability Reference Group, 2010)

Design for all is a concept rooted in European tradition. Its defining goal could be worded as "a product is made to be usable by the widest possible range of people," while not implying that one solution could in fact suit all. In the information field, the practical outcome should be that a product or service is usable by most users without any modification, easily adaptable to different users (customizable interfaces), and having standardized interfaces that can be accessed by specialized interaction aids. (Persson et al., 2015)

Universal design originates from the US and was named by architect and designer Ronald L. Mace. Its definition is "the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design." There are seven principles of universal design, which include equitable use, flexibility in use, perceptible information, and low physical effort, for example. (Persson et al., 2015)

Inclusive design is a UK tradition and is similar to design for all and universal design, but has in its definition "as many people as *reasonably possible*." The term appeared in 1994. It is seen as a design philosophy and not a fixed set of criteria, not a separate kind of design but part of mainstream design. Inclusive design researchers have put effort into creating tools that businesses can use for user research and the design process, such as the "Inclusive Design Toolkit," and tools to quantify inclusion (or rather exclusion). (Persson et al., 2015; Clarkson et al., 2015; University of Cambridge, n.d.)

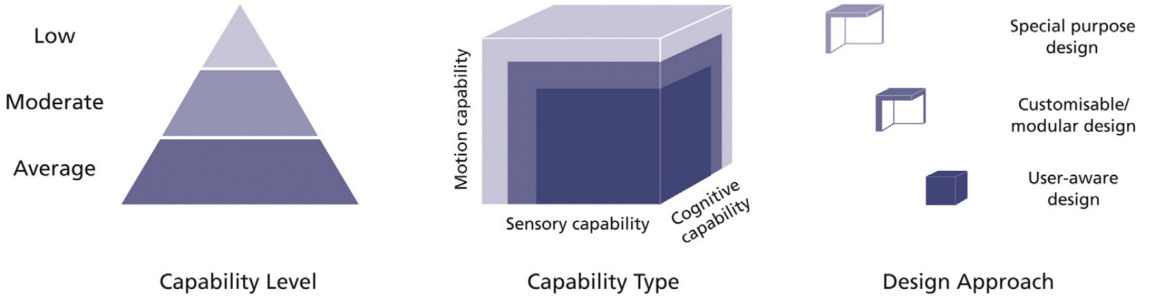


Figure 2.4: The inclusive design cube (Clarkson et al., 2015)

These approaches are merging and becoming less distinguishable from each other (Persson et al., 2015). Figure 2.4 shows an inclusive design conceptualization of people's capabilities and design approaches to cater for them.

2.3 AT abandonment problem and motivations of use

No article about AT design goes without mentioning the AT abandonment and non-use problem, which is relevant not only because of the resources waste but also because people who have had a negative experience with one AT can have pre-dispositions towards another AT in the future and miss out on possible benefits. Devices designed and distributed with the best intentions can end up in disuse for a multitude of reasons. The statistical information on how often this happens varies and depends on the type of AT, user group (children, elderly), and country, but is always a large enough percentage to demand attention. The overall average has been estimated at 30% one year after procurement. According to some studies, wheelchairs had the lowest dropout rate, while, for example, prostheses were abandoned more often. (Pinjatela, 2024)

Reasons for abandonment can be divided into:

1. characteristics of the user: physical condition, preferences, lack of training, etc.;
2. characteristics of the assistive devices: inadequacy, inappropriateness, etc.;
3. characteristics of the environment: lack of training of experts, stigmatization, challenges in infrastructure, etc.

One of the more commonly cited reasons was lack of adaptation and individualization. (Pinjatela, 2024)

A systematic review of the use of powered wheelchairs revealed that stigmatization and self-stigmatization, limited agency and choice during procurement, and lack of training were barriers in the early phase of people's journeys, while technical problems and difficulties related to maintenance and adjustments occurred over time. A period of adjustment was observed to be common, during which people discovered the positives and opportunities that their device provided and overcame self-stigmatization, after which even a sentiment of embodiment may develop. Personalization and autonomy over the appearance of the wheelchair facilitate positive adjustment. (Fishleigh et al., 2024)

Anecdotal stories about hand prostheses — one for the narrow purpose of holding a pen for handwriting and another about a makeshift soft string contraption just for changing a baby's diapers — illustrate how, for a personally meaningful activity or in highly contextual circumstances, some low-technology AT can be preferred by the user over a technologically advanced option that kind of does everything, but none of it particularly well. (Hendren, 2020) Sometimes the motivation for use of AT may not be its utilitarian value at all, but self-expression and playfulness, as in the case of the collection of artist-made prosthetic legs owned by athlete and model Aimee Mullins (Pullin, 2009).

2.4 Conclusion

The changes that an SCI brings into the life of an individual suffering it range from severe to devastating. The exact body-function outcome depends on the injury level and completeness of the injury, as well as individual factors. Paralysis that takes away walking ability and muscle control, and loss of control over bladder and bowel function, are likely to have the most significant effects on everyday life, but a range of other medical issues also present themselves. Steep environmental barriers arise from the changed physiological state. Tetraplegia may render a person largely dependent on caregivers. C5–C7 level SCI-s fall into a range where the hands and fingers are paralyzed, but partial use of the arms remains.

People with SCI-s commonly mourn the loss of control and independence, but assistive technology — for mobility or other daily tasks — can restore some executional independence and also support decisional autonomy and participation (meaningful roles), which in turn improves QOL. Therefore, continued work on designing AT-s is necessary. Because variability within the SCI population is so large, it is reasonable to expect that generalizations across the user group are not the best path to suitable designs.

Researchers of disability and design history appreciate, in the pre-industrial era, the fact that PWD-s were directly in charge of the objects made for their needs, just as customers were in charge of all craft-made goods they commissioned. The industrial era placed designers as middlemen with preconceptions between the PWD and AT. The medical model of disability, prevalent for most of the industrial era, marginalized PWD-s.

At the end of the 20th and the beginning of the 21st century, the civil rights of PWD-s were finally formalized into legally binding policies. In design, development toward equitable ideals started with wheelchair accessibility of buildings and grew into philosophies and practical tools that aim to make mainstream products usable by everyone. This approach — design for all, universal design, or inclusive design — exists and must exist in parallel with the design of assistive technologies.

3 THEORETICAL FRAMEWORKS

3.1 Theoretical model for assistive technology: Human Activity Assistive Technology (HAAT)

The Human Activity Assistive Technology model of AT in Cook et al., 2016 originates from the first 1995 edition of their book. The model is described as ”someone (human) doing something (activity) in a specific context using technology as an enabler,” and in this format, it avoids the assumption that the technology itself meets the needs of the human. But instead, the human adapts the technology for the activity. (Cook et al., 2016)

In HAAT, assistive technology (AT) is a component in a system that involves the human, the activity and the context components as well. Each component has various elements (see figure 3.1). The AT component can be divided into a human-technology interface (inputs or contact with the body) and an activity output. A processor or mechanism is present in many, but not all, devices and sometimes there is also an environmental interface - some kind of sensor input. (Cook et al., 2016)

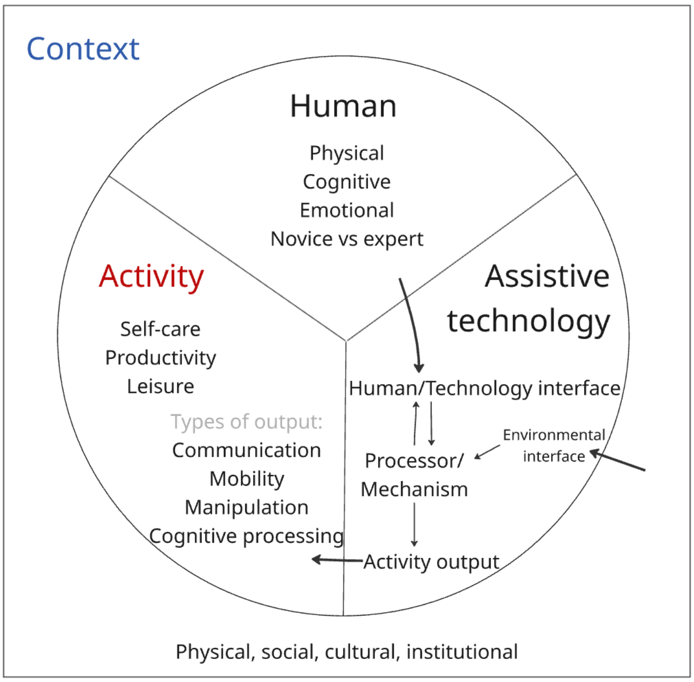


Figure 3.1: The Human Activity Assistive Technology (HAAT) model consists of 4 components and their elements (Cook et al., 2016) (adapted schematic)

The HAAT model has application in product research and development, product usability studies, client assessment and outcome evaluation.

3.2 Design for (every)one - assistive technology co-design macro framework

“Design for (every)one” is a name for a design framework concept developed by Lieven de Couvreur and his various co-authors (De Couvreur et al., 2011b; De Couvreur et al., 2011a; De Couvreur et al., 2012; Ostuzzi et al., 2017) De Couvreur has a background in cybernetics (De Couvreur, 2016). Design for (every)one was first outlined in De Couvreur et al., 2011b and motivated by shortcomings in the design process that the AT production companies use. The authors saw potential in spontaneous hacking practices by people with disabilities and their caregivers. Research for the development of the framework was done based on students’ team projects from 2009 to 2015 (De Couvreur et al., 2012; Design for everyone, n.d.).

Universal design that addresses the needs of the widest possible audience and assistive technology (rehabilitation engineering) that attempts to meet the needs of specific individuals, have opposed characteristics. Universal design embraces economies of scale, providing for maximally large audiences and is driven by market pull. Rehabilitation engineering tends to be driven by a technology push, but often fails to consider the user very well, and furthermore, the user is often not even seen as the customer. What is lacking is a contextual push to the design of AT. The authors suggest “user-driven innovation on the level of rehabilitation engineering” as a good match to community-based rehabilitation strategy that the WHO is advocating for. (De Couvreur et al., 2011b)

Three prerequisites allow such innovation to happen:

1. some users and/or their family members, friends have an incentive to innovate;
2. at least some of them willingly reveal information about their innovation to allow others to reproduce it;
3. self-production can compete with commercial production and distribution.

All three points are observed to be true. 1. People with disabilities have individual needs, and they are accustomed to improvisation for solutions; their family and friends, sometimes volunteers as well, participate in creating tools for them, either hacking existing products or building from scratch. 2. Sharing, remixing and collaboration through the internet is happening. 3. Rapid manufacturing tools enable production. (De Couvreur et al., 2011b)

The authors emphasize the ”wicked problem” nature when it comes to AT and the utmost importance of experimentation and iterative prototyping for testing with individual users. The role of the prototypes is instrumental, creating shared language between all stakeholders and supporting the continuous back-and-forth shift between questions ”what is needed?” and ”what can be built?”. (De Couvreur et al., 2011b)

Design for (every)one framework also describes three key roles (see figure 3.2) - that are not necessarily always held by three separate people.

- Key role “activity: occupational therapist” knows the medical constraints and possibilities that apply to the patient and can dissect an activity into a task sequence.

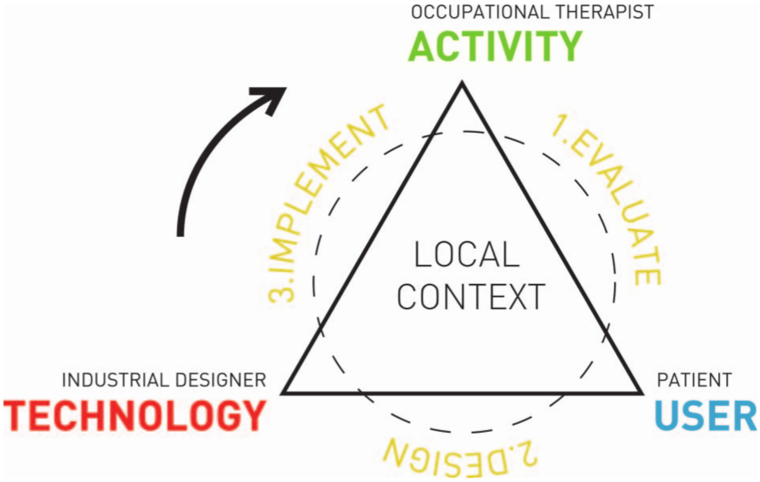


Figure 3.2: Trialogue between key roles and iterative actions in *Design for (every)one* methodology. From De Couvreur et al., 2011a

- Key role "user(s): patient/caregiver" is usually the patient - the expert of their own experience, sometimes supported by the caregiver as translator of the patient's needs.
- Key role "technology: industrial designer/user-manufacturer" has to ideate and create tools and prototypes for the occupational therapist to be able to communicate with the patient on a physical level. Also, documenting the process by the industrial designer can be valuable for the community. (De Couvreur et al., 2011b).

The mechanism how the Design for (every)one tailor-made approach should benefit a larger community is open-source sharing and cycles of re-appropriation within it. The framework provides guidelines on how to translate a solution created for one person into an open design solution. They propose dividing product properties into three categories and assembling the build instructions accordingly.

- *Defined-fixed* elements are fundamental for the product to have its function and distinguish itself from other solutions for the same problem. They should be described precisely and exhaustively for reproduction.
- *Contextual* elements "need to change in order to fit in the new context of use". They depend on the specific user and environment and should be communicated like a procedure to obtain the relevant information.
- *Undefined* elements are design choices that are not important for the solution and its recommended not to even communicate them in the instructions in order to avoid information overload.

The authors call this Open-ended design - "a project able to change according to the changing context". (Ostuzzi et al., 2017)

3.3 AT-d8sign - methodology focused on user-centered design of assistive devices

Santos and Silveira (2020) based their research on a systematic review of other methodologies and their own case study, with the goal of providing a methodology for the AT design process with concrete tools suitable for larger teams. They also say it is paramount to initiate the process as design for one, and only after reaching a satisfactory solution for the single user, in the later testing and refinement phases should more users be involved. The team is expected to be made up of the user, different industrial professionals, relevant medical professionals, and other stakeholders such as caregivers. A design cross-domain has to be established, preferably in face-to-face meetings, and by sharing field knowledge with the whole team. It is important to keep the user motivated to participate throughout the longer development process. The formation of trust bonds between the user and the team, and follow-ups throughout the adaptation period, is suggested to reduce the likelihood of abandonment. (Santos et al., 2020)

After the first phase of establishing the team and creating a shared design cross-domain understanding, there will be two simultaneous cyclic processes (see figure 3.3). The conception spiral involves design requirements definition, with ranking of the requirements, followed by concept generation. The authors recommend using tools and techniques common in industrial design, such as Quality Function Deployment ("House of Quality"), functional analysis, Material Energy Information diagrams, morphological analysis, Failure Mode and Effect Analysis, as well as biomimetics and TRIZ problem solving. The possible solutions created should be discussed in meetings, balancing between "ideal", "possible", and "necessary" from the perspectives of cost, manufacturing, materials, time, etc. (Santos et al., 2020)

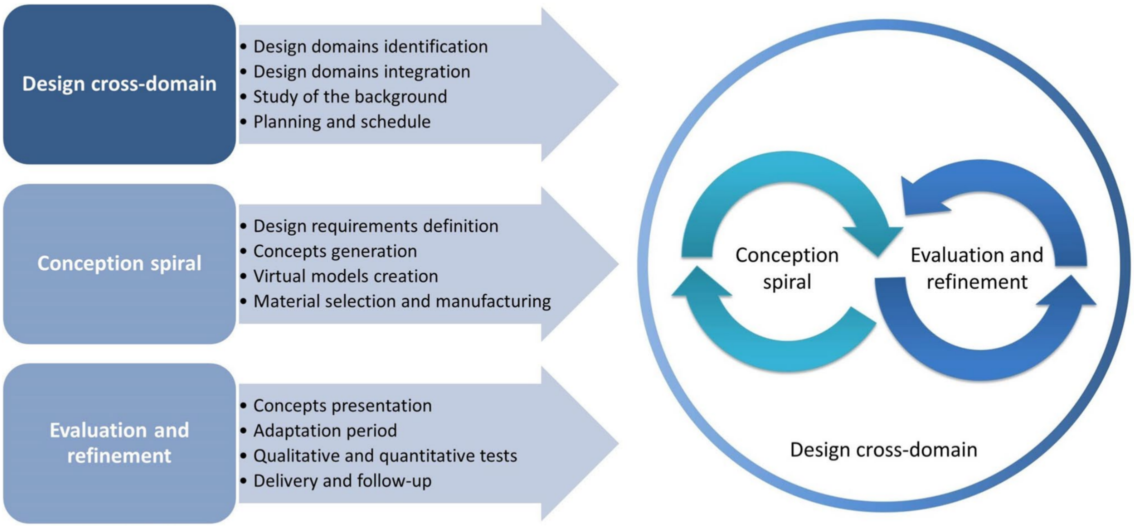


Figure 3.3: The proposed AT-d8sign method, its phases, and stages. From Santos et al., 2020

The evaluation spiral involves concept presentation in the format of sketches and drawings, virtual models, and physical prototypes, depending on the progress of the project. Alternative intermediate materials can also be used for prototyping — clay, playdough, Lego, etc. It is important to record feedback and suggestions from the user and the team. The decision to close the re-design and refinement cycles and move on to final delivery will be based on many factors, but the end user should always be the central criterion. Even though the guidelines clearly address industrial product development, the authors do mention a possibility of distributing the project as open-source CAD files as well. (Santos et al., 2020)

3.4 CoDEA - framework for co-designing 3D printed assistive technologies

Aflatoony and Lee (2020A, 2020B, and 2023) attempted to develop guidelines for collaboration between an industrial designer (ID), an occupational therapist (OT), and an end user for assistive device "design for one", through a series of four experimental workshops. They compared outcomes from workshops where ID-s were acting as "technical facilitators" to ones where they were encouraged to be "design thinkers", and found the latter to have produced higher-quality artifacts. (Aflatoony et al., 2023)

Based on the observations and reflections of the participants, the authors suggest that such collaborative workshops progress through stages (see figure 3.4) where people in different roles should take the lead. The OT is in charge of communicating with the user in the first stages for clinical need identification and AT problem identification. Then the ID starts to lead the conversation in the exploration of AT solutions; the designer's task is to propose solutions, obtain feedback from other participants, and encourage co-ideation. First, low-fidelity prototypes are created; then 3D-printed solution iterations are made. The OT is in charge of examining and evaluating the result with the user, and likely another iteration realized by the ID will follow. The proposed framework is named CoDEA: a framework for co-designing 3D printed assistive technologies. (Aflatoony et al., 2020; Aflatoony et al., 2023)

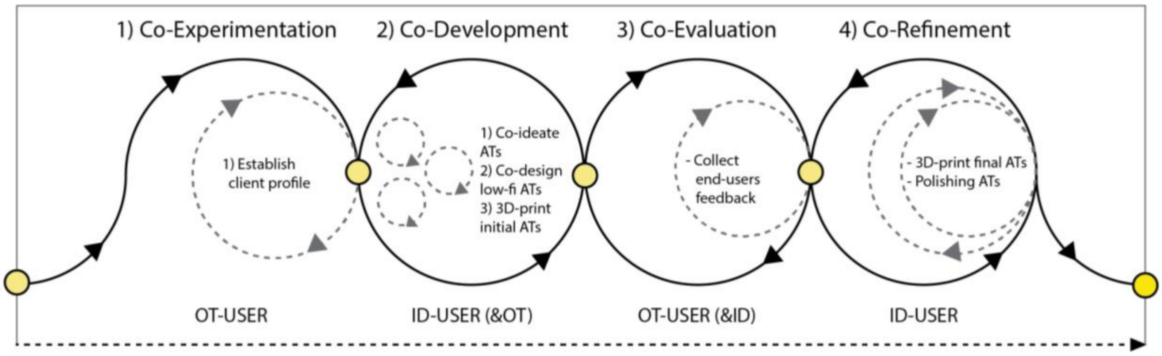


Figure 3.4: CoDEA: Co-Designing 3D printed Assistive Technologies with OTs–IDs–Users. From Aflatoony et al., 2023

The main value of such three-party collaboration is seen in co-optimizing experts' knowledge and mutual learning. But this framework does not contain any recommendations on distributing the result, besides satisfying the need of the single client.

3.5 2PAC - "People Person Activity Context" PD framework

One research question of Barbareschi, 2018's doctoral thesis is "How can the impact of disabled users' participation in the [participatory design] of ATs be maximized?"

Barbareschi states the following issues as common for PD:

- An unclear definition of the problem that PD is trying to solve is a barrier to meaningful participation.
- Members of the design team who are recruited from the target group will become more informants and less co-designers if the professional designers and researchers in the group have not established a thorough understanding of the topic. They also tend to feel that their inputs are not taken seriously by professionals.

To overcome these problems, she suggests her framework "People Person Activity Context" — 2PAC — where she argues for a clear separation between research and design phases (see figure 3.5). The process starts with identification of a problem that could be solved with new AT. The second phase is "Analyze", which in turn contains four elements that aim to cover the human, activity, and context of the HAAT model (see section 3.1). Barbareschi collected 19 questions from a multitude of AT adoption models that may help analyze these four areas. Then, before starting the design itself, the results acquired in the Analyze phase must be shared with all design team members to create common ground knowledge, but the format should be very concise. Finally, the design phase must, on the one hand, be kept short to reduce the burden on participants with disabilities, but, on the other hand, "evolve from a general description to a physical prototype". Additionally, to avoid power imbalance, members of the design team should moderate the design process rather than actively participate in it. (Barbareschi, 2018)

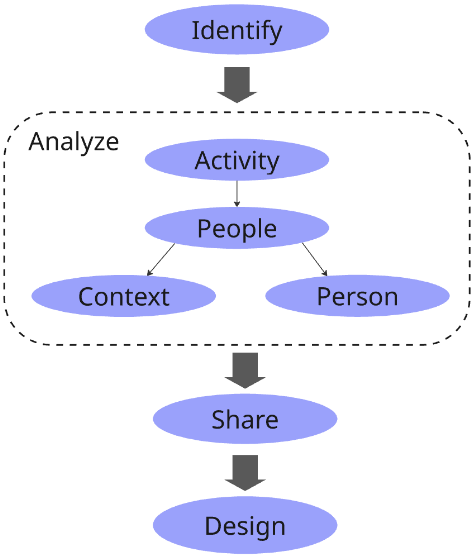


Figure 3.5: Sequence of phases in the 2PAC framework. From Barbareschi, 2018, adapted.

3.6 Other authors on related topics

A multitude of volunteer networks, that are providing AT tailor-making service for PWD-s, exist in maker culture, and many authors perceive them as positive (Luck, 2018; Wilson et al., 2023; De Couvreur et al., 2011a). Yet some criticism and caution has been expressed by OT-s and prosthetists regarding the safety of DIY solutions (Hofmann et al., 2016). A second direction of criticism addresses situations where AT is used simply to showcase new technologies' capabilities and is done without ever involving the PWD-s themselves (Williamson, 2020). Similarly, crip technoscience condemns the attitudes and language of some maker organizations that paint a picture of PWD-s as unable to contribute to creative work (Hamraie et al., 2019).

3.7 Conclusion

In this chapter, an overview was given of four different suggested design frameworks addressing the design of AT. Table 3.1 compares the previously described frameworks. Three of them were built around the idea of "design for one" — taking one individual user's problem, solving it for that user, and only then looking into who else could benefit from the solution. The Design for (every)one framework tapped into the observed phenomenon of spontaneous hacking that takes place in family and friend circles, or by volunteers, and imagines an open-source sharing and re-appropriation ecosystem. It also notes that in designing for AT there is inevitably an "occupational therapist role", be it fulfilled by a professional OT, the user themselves, or their caregiver, utilizing their knowledge of the health state, abilities, and needs of the user. Design for (every)one's main ambition is to help open-source sharing of AT solutions prosper, but it also recommends that industrial design follow the design-for-one principle.

The AT-d8sign framework comes from the context of industrial design for production, where several engineers may need to collaborate. It suggests involving one individual user, their related stakeholders, and necessary medical professionals in the team, and establishing a strong knowledge base shared by the whole team before proceeding to design, prototyping, and evaluation.

The CoDEA framework responds to the opportunities of 3D printing and aims to co-optimize OTs', IDs', and users' knowledge via communication strategies and roles. The focus seems to be on the context of OTs' work with clients one by one, and not on extending directly to industrial design.

The final framework, 2PAC, addresses co-design and tries to solve the problem of the burden of participation on PWD-s and power imbalances. It suggests extensive research be done beforehand, and its results shared with co-design workshop participants in a concise format. It is not as thorough as the other frameworks, as it describes the process up to a co-design ideation workshop involving PWD-s and designers (but not OT-s), and does not go into development and testing phases. It is included in the list mainly because the subject of the study was wheelchair transfers, and the caveats of co-design brought out are worth consideration.

For the purposes of this thesis, the central ideas mixed and matched from these frameworks and articles were the following:

- Design for one.
- An ideation team consisting of a user, an occupational therapist, and a design student (me) — the three roles in Design for (every)one.
- Utilizing the expert knowledge of an occupational therapist — as in AT-d8sign and CoDEA — and avoiding accidental harm, as warned by Hofmann et al., 2016.
- A co-design workshop held with material visualization aids, inspired by the systematic review section of the AT-d8sign article and largely overlapping with the 2PAC experiment.
- Using low-fidelity prototyping during a co-design session, as in AT-d8sign, CoDEA, and 2PAC.
- Proceeding to building and testing full-scale prototypes to follow the central premise of Design for (every)one, as well as AT-d8sign. The timeframe and scope of the thesis did not allow for more than one iteration, though.

Table 3.1: Comparison of previously described frameworks of design for disability

Source	**Topics and participants**						**Vision for distribution of designed results**	**Summary**
	Design for one	OT(-s)	ID(-s)	Maker(s) / volunteer(s)	Rapid prototyping tech.	Iterative prototyping		
Design for (every) one de Couvreur et al 2011, Ostuzzi et al 2017	✔	✔	✔	✔	(✔)	✔	Open source, (production business)	Designs "for one" done by makers or professional teams evolve through re-appropriations to next users.
AT-d8sign Santos&Silveira 2020	✔	✔	✔		✔	✔	Production business, open source	Design should be done "for one" initially, by multiple domain team, with product development tools. Later prototypes can be tested on many users.
CoDEA. Aflatoony&Lee 2020A, 2020B, 2023	✔	✔	✔		✔	✔	None	Collaboration between occupational therapist and industrial designer to make "for one" AT. Recommendation to shift the leading role between OT and ID depending on phase.
2PAC Barbareschi 2018		✔					Open source	Framework for participatory design that minimizes burden on PWD-s. Preparatory research, then PD workshop, where the main team takes a moderation role.

4 METHODOLOGY

Initial goals, research aim and research questions. My goals when starting the thesis project were to design a physical product in the category of disability AT and have people with SCI-s as the user group. The research aim and questions, as already stated in the introduction, are following:

The aim of this thesis is to explore challenges people with tetraplegia face in wheelchair transfers, through a co-design and prototyping process, in order to inform the development of a transfer aid.

1. What are the key physical, social, and personal factors shaping the experience of wheelchair transfer for people with C5–C7 level tetraplegia?
2. What priorities and requirements, from the perspectives of people with tetraplegia and caregivers, emerge from co-design activities within a design-for-one context?
3. What does iterative prototyping contribute to the understanding that verbal and visual communication alone do not reveal?

Literature and desk research. I started the literature research with books about design for disability that give a historical perspective on how various aids have been made and distributed, as well as a critical view of the attitudes that have motivated the design processes of AT-s. An introduction to what life is like for people with SCI was acquired from a couple of books/booklets written with the purpose of being handed out to patients who are in active recovery from a recent SCI. These booklets focused mainly on the biological–medical aspects. Scientific articles on various topics surrounding life with SCI filled in the psychological dimension to some extent.

I used mapping to create a more connected understanding of the knowledge acquired from the literature. Maps were made of the following: medical aspects of SCI; how design relates to necessary care and independence of PWD-s; activities of daily living for a person with SCI, stakeholders, and four categories of autonomy (from van de Ven et al., 2008).

To inform the design process, several authors' articles were collected on the topics of co-design and incorporation of rapid prototyping in the fashion of DIY ("do it yourself") / maker culture into the design process. As an overarching topic in the historical overview had been the little involvement of PWD-s in designing, and as a response to that, the latest work seems to converge on participatory design practices as the recommended approach.

In the later stages of the project, scientific articles on wheelchair transfers were studied, though some information in some of the articles was too specialized for me to fully understand. I researched existing transfer AT products and patent databases for suggested solutions. The retrieved results of the state of the art were used for the individual thought process and as a discussion aid in the co-design workshop.

Observation at occupational therapy sessions. The Haapsalu Neurological Rehabilitation Center, and a number of patients there, kindly allowed me to spend a day as a job shadow of an OT and gain valuable firsthand insight into transferring as a physical skill and some of the difficulties that people may face.

After the observation and a conversation with an OT, it was decided that one possible realistic thesis project goal could be a wheelchair transfer aid for people who deal with tetraplegia that involves weak hands (C5–C7 level injury), or some other aid device for that group.

Semi-structured interviews. Three interviews were conducted with people who have been living with tetraplegia for 18 or more years. The group consists of similar individuals; they are not a cross-section of the population, however they represent one major sub-group: men injured at a young age at the cervical level of the spine. After conducting all three interviews, the topic was locked onto wheelchair transfers.

Co-creation workshop. One of the interviewees was chosen, and a co-creation workshop was held with him and an OT. The participant had a very concrete problem of not being able to transfer out of his car without seeking the help of a person physically stronger than the family member with whom he typically uses the car. The workshop lasted three hours, during which we discussed existing transfer AT, the specifics of the problem that the participant had, and the methods by which a caregiver can assist a transfer. A few ideas for new AT emerged during the workshop, and at the very end of it I presented three concepts I had prepared in cardboard model form. Two ideas — one from the workshop and one from among my models — were chosen by workshop consensus for further development.

Prototypes and testing. I built the two ideas into full-size functional prototypes. Another meeting was held with the same participant and the OT. Sadly, one of the prototypes broke after just one demo, and we could not test it in a real situation. The OT tested the second prototype, but it seemed to be lacking too much to be tested safely with someone with tetraplegia. Another testing took place with the supervisor of this thesis, who is himself living with tetraplegia, and his family member caregiver. This time, the first prototype was tested in a real-life situation, and I gave a demonstration of the second prototype. The conclusion from the testing was that I should focus on one short phase that tends to be physically challenging for the caregiver at the beginning of a transfer out of a car.

Concept proposal. The final concept differs from both of the prototypes, but utilizes a technical approach that was already present in one of them. It targets the phase of car transfer that was revealed as the most problematic during the testing.

5 DESIGN RESEARCH

5.1 Interviews with people with SCI

The questionnaire for the semi-structured interviews was assembled with the intention to learn broadly about everyday life with SCI and to keep the topic area of the design solution open, but as I already had an initial interest in wheelchair transfers, several questions targeted this area. The questionnaire is shown in appendix 1. Questions were asked in the same order to all participants, though some wording of the questions changed according to context. Additional topics that came up were welcomed, and clarifying and follow-up questions were asked where I saw a reason to do so. To keep the identities of the participants confidential, in the following text some categories of information are intentionally written in a way that does not allow tracking one person's answers through all topics.

5.1.1 Demographics, home, family

Three interviews were conducted with people who had suffered spinal cord injuries and were living with tetraplegia as a result. All of the interviewees were male, aged 36 to 50, had suffered the injury at ages between 18 and 25, and had lived with tetraplegia for 18 or more years. They were all living in Tallinn, and their homes were in buildings that were either constructed recently, with requested accessibility features, or private houses that had been modified over the years to become wheelchair accessible. Therefore, exiting their own homes in a wheelchair was not a barrier for the interview subjects. This characteristic is not representative of all people with SCI-s. The occupational therapist practicing in HNRK said that the majority of people with SCI-s in Estonia exit their homes once a year for therapy in HNRK, because of the inaccessibility of the buildings they live in (personal communication, 13.12.2025). All interview subjects were either employed or entrepreneurs. One of the interviewees was living alone, and two were living with their parent(s).

5.1.2 Moving around

All subjects used a manual wheelchair, and all of them also had a powered wheelchair, but the types of powered wheelchairs differed for each participant. One participant had an all-terrain wheelchair that he used infrequently, only for visiting wild nature areas, as he preferred to have the physical exercise from propelling a manual wheelchair in everyday life. Another had a powered collapsible wheelchair that could be transported in the trunk of a car. The third participant had an indoor–outdoor powered wheelchair for city mobility.

Habits of using transportation outside the home differed greatly between the interviewees. One mainly used his medium-sized powered wheelchair and public transportation during warm seasons that allow the electric wheelchair to drive on sidewalks. In the case of snow, that was not an option, and he defaulted to a manual wheelchair and wheelchair taxi. All three participants occasionally used the wheelchair taxi service, which allows a person to board in any kind of wheelchair and stay in the wheelchair during the drive. In two interviews it came up that wheelchair taxi scheduling is not flexible and often has to be booked many days in advance. Another participant regularly used ordinary taxis and the Bolt ride-sharing service, instructing the driver to assist him with a transfer to the seat and out again. In his experience, this worked fine almost always. The third participant owned a car that a family member drove, and this was his main means of transportation. He had also used an on-demand wheelchair-accommodating bus service provided by the city of Tallinn for free, where a bus route is adjusted to transport multiple people simultaneously to their destinations.

5.1.3 Daily activities, assistance from family members, and assistive devices

Two participants rely on their parents for daily activities such as getting dressed, wheelchair transfers, hygiene-related activities, and cooking. One participant is independent in daily activities when at home, but keeps a running list of tasks that need doing to delegate to a hired personal assistant who visits regularly. He also admits that getting dressed and undressed takes a lot of time when done on his own — 1.5 hours — but he has a routine and listens to news, books, and podcasts while doing it. He does not mind that cooking takes time, as it is an enjoyable activity.

One participant has a transfer lift device installed in the bedroom, along with an assistive bed (motorized lifting into a sitting position) and another lift in the bathroom, which he uses with assistance from a family member. Another has a lift in the bathroom for independent use. Another participant has an assistive bed and performs transfers with a family member, some with and some without a transfer board.

Two participants use an assistive device that helps grab small items that are otherwise out of reach — on the floor or on higher shelves.

One participant expressed a strong belief that he wants to avoid assistive devices, because relying on them makes him dependent on them and more helpless outside the home, where the same things are not available. He prefers to learn to do things without assistive devices where possible and to include them only where well justified.

5.1.4 Asking strangers for assistance

All participants regularly ask for help from strangers in grocery stores — to reach items on shelves and to package them after checkout. It is also common that when using a manual wheelchair outside the home, there are small inclines and curb cuts that require more force to climb with a manual wheelchair than tetraplegics with weak hands can exert, and they ask passers-by to push them briefly. Experiences with this kind of asking were positive; people had always been helpful. One participant also noted that this kind of "little help" makes the helper happier afterward, whereas relying on one and the same person for every small need would be tiring for that person.

One participant often uses taxis and needs help from the driver to transfer in and out of the car. This has also always gone well; only once had there been a driver whose health did not permit lifting, and the driver solved the situation by calling a replacement taxi. Sometimes taxi drivers seem slightly disappointed that the ride is relatively short and involves extra work with transfers and loading the wheelchair into the trunk, but the participant felt that casual conversation during the ride improves the driver’s mood.

A possible issue with help from strangers came up in one interview: an overly eager helper can put a wheelchair user in danger. Therefore, it is important to express one’s needs clearly. People who want to be helpful should first listen and not invent what to do on their own.

There was only one story of not receiving help while being in a helpless condition on the street. During the nighttime, none of the passers-by dared to approach and ask what was needed, and therefore no opportunity for verbal communication arose.

5.1.5 Transferring

One participant transfers with a family member and a transfer board into his own car, but transferring out of the car back to the wheelchair is difficult for them. They find additional help each time to do that.

Another participant had an accident falling off a lifting device at home while using it alone. Since then, he has preferred not to use the device independently again.

The motivation behind installing lifts at home was recognizing that family members tend to strain themselves, not necessarily because strain is unavoidable, but sometimes due to a lack of patience to perform all steps in the safest manner. The cost of the devices was also a factor in when they were finally installed.

The third participant uses a lift in the bathroom on his own. He performs bed-to-wheelchair and vice versa transfers without lifting devices or a transfer board. For car transfers, he asks for help from whoever is available, for example, a taxi driver. He also needs assistance when he wants to use his powered wheelchair, which has a higher seat than his manual wheelchair and is parked outside the apartment.

One participant did not mention car transfers in the interview.

Motorized lifts at home can serve various purposes — for one participant, the bathroom lift enables independent living; for another, the main purpose is protecting the health of a family member. The number of transfers performed per day is relatively low, ranging from two to four.

5.1.6 Health and perceived dangers

Pressure sores from the wheelchair seat are a risk that participants keep in mind. One spends a couple of hours in bed in the middle of the day when possible for this reason. Another described feelings of disappointment when skin issues require spending several weeks on bed rest to heal.

Two participants viewed transferring using one’s own strength as having health benefits, even though only one of them practiced it regularly.

Falling was a common occurrence but not a particular source of fear. Two participants experienced more falls at home, while the third reported that falls typically happen outside the home. Spasticity was a familiar cause of falling out of a wheelchair for one participant. Uneven floors or ground can also cause falls.

Transfers are an activity with a heightened risk of falling.

"While I was learning to transfer independently, people had to pick me up from the floor many times. Now and then the neighbors still come when I become too brave or let my mind wander. It (falling) happens when you become arrogant."

One participant said that the only kind of fall he fears is falling backward with the wheelchair and hitting his head, which has happened to him. Falling from a transfer lift is also a danger; one participant had an accident in which his upper body fell down while his legs remained entangled in the lift. None of the participants would be able to get back into a wheelchair from the floor on their own.

A fall does not need to end on the floor to put a tetraplegic person in a helpless situation. Uneven ground or spasticity can cause a person to tilt too far forward or sideways in the seat, such that their arms, lacking triceps strength, are insufficient to push the torso upright.

Other dangers mentioned included hot water and joint injuries occurring during exertion, because pain signals from the hands does not get through.

One participant keeps his mobile phone on his lap at all times so it does not end up on a table when he falls and cannot reach it. Another once escaped a helpless situation by being able to make a call with a smartwatch.

5.1.7 Autonomy

Autonomy has several facets (literature discussed in 2.1.5), at least two came up in some of the interviews. First, finding out what kind of executional autonomy is achievable, can be a long and unpredictable journey.

The participant described the most life changing event happening more than 15 years into living with the SCI, that he had spent believing that he can't ever get dressed on his own. He accidentally saw another person with similar injury dealing with socks. That event triggered for him learning new activities and huge gain in independence that he values a lot. In another context he touched on the topic of beliefs and goals:

"If you have a wrong kind of wheelchair, you won't be able to push it freely, and you feel that you don't have the strength. And then you don't even start wanting to."

Secondly, choices between executional autonomy and participation are to be made and different people make them differently. Another participant felt the constant conflict between executional autonomy and other priorities:

"I also go to the therapies in Haapsalu and in fact you can actually get dressed, it takes an hour and a half, but it's doable. But if someone can do it for me in 15 or 10 minutes, then I'm taking the easier route. ... All these showers and going to the toilet, all of them take longer than an average person. In the end, half a day has passed, but nothing has been done besides dealing with the bodily functions. There's this feeling all the time

that I should manage more on my own. That feeling stays all the time. I know I could actually do more. That's how it is. It remains unresolved."

One participant described living in his home as feeling all-powerful in the environment built for his needs, while going to visit a close family member automatically puts him in a helpless state, needing assistance for many things starting from even getting through the entry door.

When asked about positive moments, all participants had the experience of learning skills that were temporarily lost after the injury, like feeding oneself, brushing teeth and other activities of daily living, turning oneself on the bed, doing a transfer with a family member only. They saw learning as an ongoing process in their life. One of the participants mentioned that this kind of learning often sprouts from hearing from someone else in a similar condition, that they do something in such and such manner. Another one said that his steepest progress happened, when he consciously decided to start to look for activities, a job that he would be able to do.

5.1.8 Experiences and preferences regarding assistive technology

Experiences with assistive technology were probed with questions about wheelchairs that they own now and have owned previously. Overall participants were happy with the wheelchairs they had owned since the beginning. The lifespan of wheelchairs is relatively long, two participants had had one chair for 12 years, one said he has to think ahead 5-6 years when choosing a new one. One had a negative experience with power assisted wheels that broke, were taken to repairs but never got repaired in a period of a year. Properties to consider when choosing a new chair were: suitable level of support for the person's body, because they spend whole day in it; fitting measurements and light weight in case of manual wheelchair give freedom to move, but a randomly assigned wrong size chair can induce helplessness. Choice between different types of wheelchairs includes questions where can you go with it and how it affects health in the long term. Manual chairs promote healthy exercise, but propelling is hard work for tetraplegics. A typical curb cut is too steep to climb. Electrically powered chairs come in very different sizes, it has to be considered if it fits inside the home, most can't be transported by a sedan car, but they give more independence and range in city landscapes in seasons without snow. Manual wheelchair can be lifted up stairs by a pair of people, most electric ones are way too heavy. Some powered chairs have a function to raise the person into a standing position, which is a recommended healthy exercise. Even if the wheelchair is collapsible, it might have too large battery capacity for taking it to air travel. In conclusion there are very many options regarding wheelchairs and choices have to be made about several priorities.

The questions about possible future assistive technology were: "based on which properties would you decide to use or not use a transfer aid device?" and "is there anything else you want me to know when designing a transfer aid?" and snippets of answers to some other questions also informed this section.

All three participants emphasized that the space at home is limited and valuable and large objects are not welcome. Two of them also wanted to keep their home looking like a normal home as much as possible, where the disability aids would not ruin the visual aesthetics. One participant prioritizes ability to use a device on his own and it's safety. The other two did not bring up safety, possibly assuming it is an obvious consideration or possibly having an attitude that every activity involves risks anyway.

One participant expressed his belief that assistive technologies should be used as much as needed, depending on the specific injury and progress of recovery, but as little as possible.

5.1.9 Experiences with inventing solutions and designing for oneself

Picking up items with hands at home was described as a context in which improvising solutions is common - all participants have limited use of their hands. Items falling on the floor or located on higher shelves pose problems. There is a device available that extends the length of the arm and has a grabber in the end. But everyone had experiences of improvising.

One participant had added an extra part at home to a handle of a shaving device for it to stay in his palm. Another had gotten help from occupational therapist to add loops to a broom and dustpan to be able to use them without the ability to grip with his fingers. One had gotten advice from occupational therapist to use anti skid mats under hands when transferring. One had made with the help of other people a transfer board out of wood when he arrived to holiday location and discovered that the usual transfer board had been forgotten at home. He now uses that handmade board at home.

5.2 Moving from one seat to another: independent and assisted wheelchair transfers

5.2.1 Standing pivot transfer

When a person without mobility limitations moves from being seated in one location to being seated in another just nearby, the body's mechanical process goes as follows: the person might adjust their seating position so that they are more on the front edge of the chair and place their feet symmetrically and close to the chair. They lean their torso forward bringing it into somewhat bent down position which places their center of mass vertically right over their feet. Then they start to straighten their knee and hip joints simultaneously which brings them into standing position. Then they move their erect body with some steps so that their backside is in front of the destination (target) seating surface. The movements to get seated down are approximately a reverse of getting up.

When a person with limited strength in their legs or with balance issues does the same process they try to find a way to support and push or pull up themselves with their hands, either on armrests of a chair or anything else available nearby. Sometimes straightening to fully erect standing position is not optimal if the target seat, for example wheelchair, is nearby, instead keeping oneself bent enough to keep holding on to armrest might be preferable. Then a turn around a vertical axis needs to be accomplished with some steps. The turn may require changing the grip on objects as well, for example to the other seat's armrests. A sequence that involves at least mostly straightened legs is called a standing pivot transfer and this can not be done by someone with complete SCI. It is described here for comparison purposes only.

5.2.2 Sitting pivot transfer

When a person with paralyzed legs - someone who has suffered motor-complete SCI resulting in paraplegia - needs to move from one seat to another, the best setup is the seats touching each other and no armrests between. Many wheelchairs allow removing the armrests for this reason. Also the ideal condition would be where the seats are exactly the same height and there is no gap between them.

Wheelchair legrests are often made in a way that allows them to be removed or moved away to the side, so that feet of the person transferring can be supported on the ground close to the wheelchair seat - this is an important step in preparation for sitting pivot transfer, to place feet where the center of mass will be during the move.

Transferring horizontally can be done by lifting the weight of the upper body with both arms just enough for the buttocks to lose contact with the seat surface for a moment and during that brief lift the arms can push and pull the body also sideways so that landing back happens in a new location. The optimal way to momentarily lift the torso is to be seated close to the front edge, hold on to the front edge of the seats with already straightened arms, and do a dynamic forward ”rocking” motion with the torso. When the center of mass is moving forward it moves onto the arms automatically. This does not require the same muscle capacity as lifting a body up by straightening bent elbows.

At the same time part of the body weight is supported to the floor via the legs, so the lifted mass is not quite the full body mass. The feet are best placed into a position that is not symmetric for the initial seat, but more of an intermediate between the initial and target seated positions. That means the foot on the side of the target seat is extended forward on the floor.

If the hand on the side of the initial seat (trailing hand) is placed close to the body and the hand towards the seat they are heading to (leading hand) is placed further away from the body, then the sideways pushing and pulling is easiest to do compared to other possible placements for the hands.

This method of transfer is commonly used by people with paraplegia or other impairments who can’t stand up on their own but can use their arms sufficiently for this method. In real life situations the seats are rarely right next to each other without gap, instead typically a wheelchair is parked next to the other seat at approximately 25 degrees angle (Gagnon et al., 2009). This placement is optimal for the feet on the floor to receive part of body weight as described earlier. The seats might not be level with each other as well. Therefore more realistically a transfer often has to happen as a single swift lift and pivot movement that clears a horizontal, sometimes also vertical gap between the chairs, while the person’s body turns around a vertical axis at about the feet and leaned forward shoulders location. See figure 5.1 for schematic. This kind on one swift transfer is called a sitting pivot transfer.

A person with for example C6 level tetraplegia can’t hold on to the edge of the seat with their fingers nor keep their arms in straight position - that would require triceps muscles. They can use a workaround where they rotate their straight arms outwards and lay palms flat on the surface. External rotation keeps elbows locked and allows the ”rocking” motion technique to still be used (Long, 2017). Head movements can be used to create inertia that then takes the body forward when torso muscles are not sufficient.

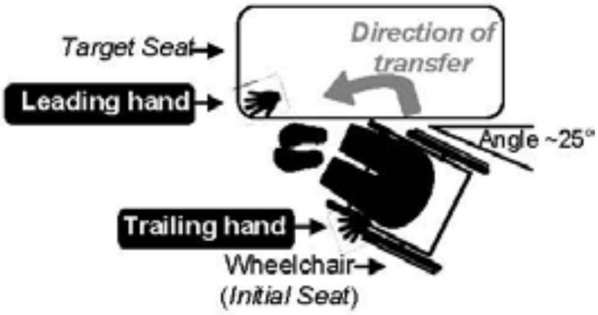


Figure 5.1: Schematic representation of a sitting pivot transfer. (Gagnon et al., 2009)

5.2.3 Transfer board transfer

If the surfaces of the chairs had no gap between them, then the full transfer could be done as multiple steps of little lifts and sideways movements. Though wheelchairs and furniture rarely make such perfect setup, it can be created with the use of a transfer board - a simple flat board, made of wood or plastic, that is placed between the two seats, resting on both and bridging the gap (see figure 5.4).

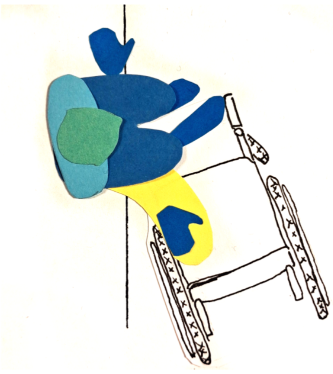
Usually placing the transfer board requires the person to first lean sideways opposite side from the target and insert the board under their buttocks on their current seat. If the height difference can be chosen for example with a motorized bed then a slight decline is ideal and the move can be done actually sliding on the smooth surface in a controlled manner, the boards are usually made of smooth material that facilitates gliding of most clothing.

In the end of the transfer the transfer board usually needs to be pulled out from under the seated person.

A sequence of an independent transfer with a transfer board is shown on figure 5.2 and 5.3.

Besides independent transfers, the transfer boards are very often used with assisted transfers as well. An assistant can hold on to the belt or pants of the person transferring and create the sideways force, though it is relatively hard to simply slide a seated person on horizontal surface, often a mix of sideways and upwards movement is used. A combination of the person themselves leaning forward with momentary inertia on the transfer board as in sitting pivot transfer, and an assistant creating the sideways force can be an optimal solution for some cases where the person can’t transfer alone and assistant does not possess physical strength to quite lift them.

1

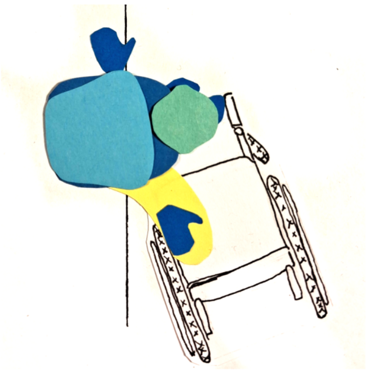


The wheelchair is at ~25 degrees angle, transfer board(yellow) underneath the buttocks and other end on the wheelchair seat.

To prepare for transfer, the feet are placed on the floor, a little bit towards the positions they should be in the end of the segment of transferring, but not far from the body's center of mass.

Arms are turned out (fingers pointing left and right) to lock the elbow in a straight position. The leading hand is placed a little bit away from the body in the direction of the transfer, the trailing hand is close to the thigh.

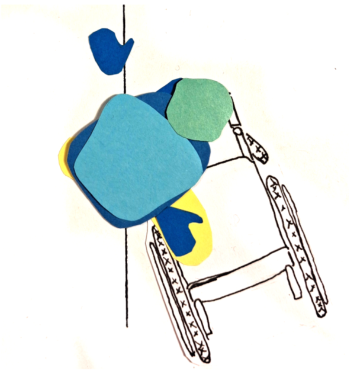
2



Rocking forward movement is made with the torso.

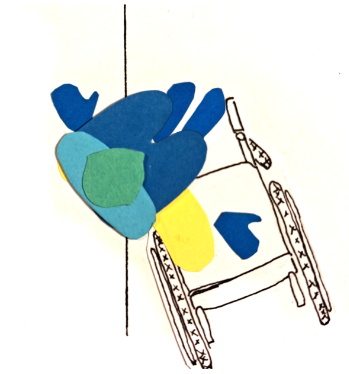
The extent of forward lean varies between people, depending on their injury level as well as level of training and skills, because getting back vertical afterwards will require strength.

3



In the far position of the rocking movement the body weight goes on the arms (and some on legs). At that moment arms are used to push and pull and rotate the body. Buttocks land closer to the leading hand than before.

4



Feet and hands position is adjusted for the next similar move.

Figure 5.2: Sequence of typical transfer board transfer done by someone with C5-C7 tetraplegia. Continues on figure 5.3.

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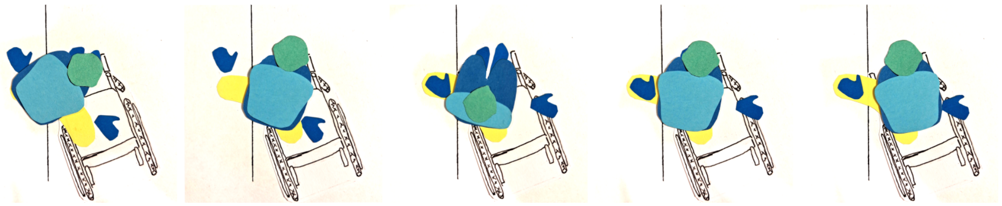

The previously described movement pattern is repeated as many times as necessary.

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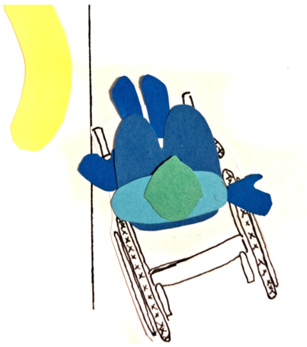

When all the step-by-step movements are done, the person is sitting on the front edge of the wheelchair seat.

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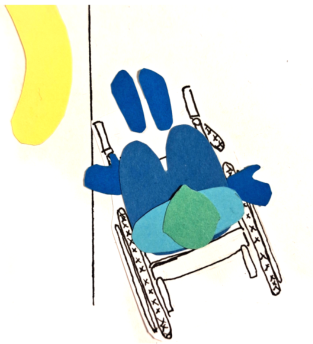

Transfer board is removed. The position of the feet is adjusted.

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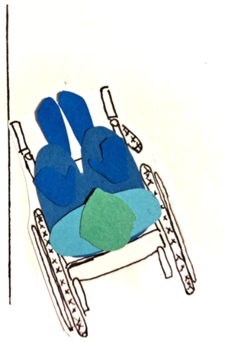


Seating position is adjusted to further back on the seat, back against the backrest. Feet are placed on the footrest.

Figure 5.3: Sequence of typical transfer board transfer done by someone with C5-C7 tetraplegia, continued.

Figure 5.4: Examples of transfer boards: a) wooden (Hausmann Industries, n.d.), b) plastic (Etac AB, n.d.) and c) BeasyTrans board with sliding seat (BeasyTrans Systems Inc, n.d.)

5.3 Existing assistive technology solutions for transferring

Existing technical solutions for transferring fall into two broad categories: those that theoretically can aide independent transferring and those purely meant to reduce the physical burden of the caretakers when transferring a patient. Some devices have to be operated by a second person therefore lie in the caretaker category. But anything that a wheelchair user can use for independent transfers, can in some circumstances be used in teamwork between the wheelchair user and a caretaker. Following is not a comprehensive list of existing products and patented ideas but an attempt to map the solution directions that have been tried. Some devices that are not suitable for people with tetraplegia are mentioned for the mapping purposes.

5.3.1 Transfer board

The overall concept and use of a transfer board was described in section 5.2.3. It is probably the most widely used category of transfer aid suitable for both independent and assisted transfers. Usually the flat board is made of wood, plastic, composite or other sturdy and reasonably slippery material, somewhere around 30 cm wide and anything between 50 to 100 cm long. The commercially available options are rectangular or various curved shapes (see figure 5.4 a and b), optionally with slots to act as handles, optionally with cutouts to anchor around the wheel of the wheelchair and prevent unexpected movement of the board. A transfer board allows to accomplish a transfer between seats of not too large height difference either in small steps or sliding, for independent transfer or with an assistant. A small decline of heights is ideal setup, incline can make the job much harder and too large decline or incline can cause dangerous uncontrolled sliding. It must also be noted that using a material with extremely low friction to clothing would become a fall hazard when slipping off in wrong direction. Non slippery board on the other hand, though it might seem smart for incline transfers, would require more physical effort to use and can injure the skin of the user (Barbareschi, 2018).

Products and ideas branching from transfer board:

- There is a product that intends to make the sliding easier by incorporating a seat that pivots in it's place and slides plastic-on-plastic, rather than relying on the clothing to interact right with the board material (BeasyTrans Systems Inc, n.d.) (see figure 5.4 c). And similar ideas as patents (Brantman, 1991; Suzuki, 2023)

- Collapsible for smaller transport size (Dyer et al., 2017)
- With articulated pivot for adjustable curve shape (Sabine, 2001)
- Permanently or semi-permanently attached to bed (Tanaka et al., 2012) or toilet seat (Cervi, 2007)
- With some combination of legs that either support it partially or make it freestanding (Toshiaki et al., 2009; Cai et al., 2022)

Despite it’s small size a transfer board might still be difficult to use in very tight conditions like a small toilet stall where the wheelchair can’t be aligned in preferred manner.

5.3.2 Lifts and hoists with a sling

In the other end of the spectrum of transfer assistive technology there are various patient lifts and hoists that are most often utilized in hospital environment. To lift a person who is very weak into a wheelchair a full body sling made of sturdy textile is placed under the person lying in bed, usually by rolling them on one side and then back onto the textile sling. The shape and attachment points of the sling make the person go into a sitting position when a powered device lifts it, and then the person can be lowered into a wheelchair (see figure 5.5). The sling is kept underneath them for the whole duration, til transferring back to bed. Lifting devices for full body slings can be freestanding on wheels - also called mobile hoists - or ceiling hoists that have permanently mounted overhead tracks for horizontal transport. A mobile hoist has to have a large wheelbase not only to fit around a wheelchair, but also to ensure balance at all times of use, because the center of mass is quite high from the ground during operation and the degrees of freedom between the lifting arm and the person. The lifting upwards motion is created either via an electric actuator or manually pumping a hydraulic cylinder by the caretaker.

Figure 5.5: Patient transfer sling and Hoyer lift device (Heal Well Medical Supply, n.d.)

Figure 5.6: Left: Handi-Move SureHands Body Support (Handi-Move International, n.d.). Right: UpLyft self transfer system (UpLyft Inc, n.d.).

5.3.3 Motorized transfer aids suitable for self transfer

I identified four distinct approaches to the body positioning among products and patent applications for powered self transfer aids.

Lift while remaining in seated position. Handi-Move body support system (figure 5.6 left) has ergonomic pads for armpits on a hinged mechanism and two hooks for the thigh areas. The mechanism is kept open with a spring for easy entry, but closes gently with the body weight in. (Handi-Move International, n.d.).

UpLyft (figure 5.6 right) utilizes a more complex mechanism allowing to pick the person up or lower down in seated or supine (laying on one's back) position and change between the positions in the air. Its four flat "fingers" are articulated with multitude of joints under padded covers, one pair forming essentially a seat surface under the thighs and the other pair a backrest. Fingers and the whole lift have to move in precisely coordinated to each other manner when inserting under the person or backing out. (UpLyft Inc, n.d.)

Lift to standing. As a side note caretaker operated sit-to-stand devices and pivot aids are commercially available, they come in simple (Handicare, n.d.) and motorized forms (Arjo, n.d.), but these are not suitable in complete SCI tetraplegia cases (personal communication with OT, 5.04.2025). Independent transfer aids that propose lifting to standing exist in patent applications but not as products. Some (Yuko et al., 2017, Wilson, 2000) propose lifting through a semi-rigid harness that wraps under the armpits. The usefulness of armpit hold is doubtful - first armpits are sensitive area and secondly spasticity (unintentional movements or muscle tensions) might make it difficult to bend the knees and hips appropriately during the lowering if feet are not stabilized.

Bent forward support. There are also devices proposed which take a less obvious approach and don't lift the person into fully erect position, but instead lift the hips up from the seat but keep the torso in bent forward position, therefore eliminating non-essential movement and lifting. (Yamaguchi et al., 2015, Yasuda et al., 2008, Watanabe et al., 2012). The body weight can be distributed between a relatively large cushion under the chest and person's feet on the device's base. Center of mass stays lower which in turn reduces wheelbase size requirement. The user's arms from shoulders down can be free to operate controls of the machine - custom larger controls could be made if dexterity is impaired. While the patents are many, I haven't been able to find a commercialized product of this morphology.

5.3.4 Transfer aid as part of the wheelchair

As most transfers start or end in wheelchair, ideas on how to incorporate needed transfer aids into a wheelchair are plentiful. With electrically powered wheelchairs the playground is wider for two reasons: the wheels of the powered wheelchair aren't so large that they block the sideways path out of the seat, and the weight of a power wheelchair is already significant, there is no strong reason to refrain from adding couple of kilograms to serve an utilitarian function. In manual wheelchairs on the other hand lower weight is of utmost value. Some electric wheelchairs already allow raising and lowering the seat which is certainly useful for transfers.

For manual wheelchairs a mechanism that allows displacing the wheel temporarily from the usual position where it is required to be for manual propulsion, has been suggested (Sim et al., 2008).

5.3.5 Solutions for car transfers

Car transfers are one of the most difficult transfers (Barbareschi, 2018). Modifications and add-ons for cars to facilitate wheelchair transfers fall into a number of categories.

- A car seat itself can be put on articulated arm that allows it to move out through the door, swivel and even descend from a high vehicle to lower wheelchair level, so the transfer happens outside (Mobility in Motion, n.d.).
- Hoists that require use of a sling and a boom is mounted inside the car that does the lifting (Mobility Innovations, n.d.).
- Lift-ramps installed under a vehicle. They require a vehicle with high ground clearance and large enough interior that can be entered with the wheelchair. After rolling in with the chair the person either stays in the wheelchair for the duration of the ride or transfers to a seat inside the vehicle. (BraunAbility, n.d.)
- Mini lift aimed at larger vehicles, a plate folding out next to the car seat, lowers and raises with a motor. They require two transfers to be done by the person onto the lift and onto the target seat, but provide optimal leveling for them. (Mobility Engineering Pty Ltd, n.d.)

All of the car related solutions listed so far are serious modifications of a vehicle and therefore not very affordable. Most car transfers get done with help of other people and/or transfer boards.

One affordable aid is pivot cushion that can solve following problem: when a person transfers, for example with help of assistant, onto a car seat, they land on the seat so, that the legs are in the direction of the door. Car seats vary but are not in general made very slippery, for safety reasons, and aligning the person with the seat can be difficult. A swivel cushion provides two layers of material that pivot around a center point and ease the rotating of a seated person (Parsons ADL, n.d.). Though additionally the person is more likely to land just on the outside edge of the seat, and for exit needs to be moved to the edge again. The cushion does not help with that. As a hack, a plastic bag is sometimes used, that does not limit the directions of sliding. (Schrupp et al., 2017) Slide sheets are also available as a product, though not intended for car use. (John Preston and Co, n.d.) Such slippery materials should be removed for the duration of driving the car, for safety.

5.3.6 Other transfer aids

If assisted sitting pivot or transfer board transfer needs to be done on very high seating surfaces (compared to the person's height), the move becomes unstable if the legs are too straight or don't even reach the floor. A purpose made footstool can provide necessary elevated area. (Direct Healthcare Group, n.d.)

Among the patent applications there was a block with a horizontal handle on top that a person can use to have their wrist in a more natural position than usual laying a hand flat on seat surface. It adds a few of centimeters to the length of the arm too, but requires fingers to be able to grip the handle. (Yefimov, 2010)

5.4 Conclusion

The people I interviewed, as expected, remembered positive feelings in connection to steps they made towards increasing one's executional independence and learning new skills. Different people have different priorities when it comes to balancing executional independence and participation and a tension between these two dimensions of autonomy can remain, which aligns with the literature (section 2.1.5).

None of the participants expressed any negative feelings towards asking strangers for help - the experiences had almost always been positive and nobody mentioned any discomfort felt in those situations, or that the need to ask strangers would become a barrier. Though I would not yet assume that this is universal for everyone, because the interview subjects are living active lives and have had lot of positive enforcing experiences, while a person more new to life with a wheelchair, or somebody who can rarely exit their home, may have different perceptions.

Attitudes towards assistive devices have several facets:

- People want to avoid cluttering their homes with assistive devices, they want their homes to look normal, not like a hospital, and they don't want to lose space to large objects.
- Some people want to avoid or postpone using assistive devices, because they see a value in the non-dependence on external objects that might not always be available, and/or prefer to get more physical exercise. This likely connects to the identification dimension of autonomy (section 2.1.5).
- The assistive device might serve and protect the health of the caregivers instead.

- As seen with the example of wheelchairs, different people may prioritize very different goals and their personal ecosystem plays a role when choosing an assistive device from a range of options - like preferring manual wheelchair for physical exercise and flexible transportation with the help of other people versus using public transportation and covering longer distances with an electric wheelchair that would never fit into a car versus easy transportation in one's own car and air travel compatibility.

Therefore there is no ”one size fits all” way to make assistive technology, but also one can't expect the people needing or wanting the assistive devices to be fond of collecting multiple very contextual ones, if they would only use them rarely.

Wheelchair transfers are a serious physical challenge for someone with tetraplegia at SCI level C5, C6, C7. Even higher level SCI leaves the person dependent on others for transfers, while level lower than that means more use of arms and sometimes easier time training for independent transfers. Many people will do all their transfers with assistance, others may master them between bed and wheelchair, but car transfers are most difficult, rarely done alone. The fact is most people with tetraplegia don't drive themselves, but use a car in the company of someone, be it a family member or a taxi driver, who can assist with things like placing the empty wheelchair in the trunk and preparing it again after arrival to destination and the actual transfer if instructed properly.

Existing transfer AT tends to fall into two categories by portability: large hoist systems for use in hospital or home indoor space, and simple transfer boards that with some effort can be carried everywhere. Transfer board has its limitations when the transfer is between different height seats on the incline, which is the case with car transfers. With some sedan cars the car seat is effectively lower, with sport utility vehicle (SUV) it's vice versa. Transfer AT for cars is available in some variation, but requires modification to the car and is not in particularly affordable price bracket. Besides it's not only the vehicles that are owned by people with tetraplegia or their close family members, that they need or want to use for transportation. It may just as well be a friend's car or a taxi.

6 CONCEPT EXPLORATION

6.1 Co-design workshop

One of the interviewees was chosen for a co-creation workshop, based on the fact that he had a well-defined problem – transferring out from a car he owns, with only his primary caregiver, was not currently possible. They successfully transferred into the car using a plastic transfer board, and the fact that the car seat was slightly lower than the wheelchair even facilitated the entry. But to exit from the lower car seat every time, they had to seek help from someone in possession of more physical strength than the primary caregiver.

I took inspiration from Santos et al., 2021 systematic review list of PD prototyping materials and Barbareschi, 2018 workshop description, and brought a kit of tools and materials to the workshop. The central object was an artist mannequin doll with articulated joints. I made a wheelchair model and a car seat model in a scale fitting the mannequin (figure 6.1). I also carried the following items: corrugated cardboard, bamboo skewers, wire, string, ribbon, fabric, play dough, matches, thumb tacks, scissors, a knife, wire cutters, pliers, a hot glue gun, a ruler, and a compass. I also prepared cardboard models of three of my own rough concept ideas.

Figure 6.1: Mannequin doll, cardboard models of wheelchair and car seat used in the workshop

The workshop was held with the participant and an occupational therapist (OT). The OT was already familiar with the participant's physical capabilities and his car transfer problem before the workshop. I explained the purpose of the workshop to them and they each signed an informed consent that is shown in appendix 3. The workshop lasted about two and a half hours, plus a demo given to me at the car afterwards.

The workshop was held in an informal manner. During the first 35 minutes, I presented a series of pictures of wheelchair transfer AT that exist as products or are found in patent databases to prompt the discussion (figure 6.2). The discussion brought up some new information and fortified some previously known points.

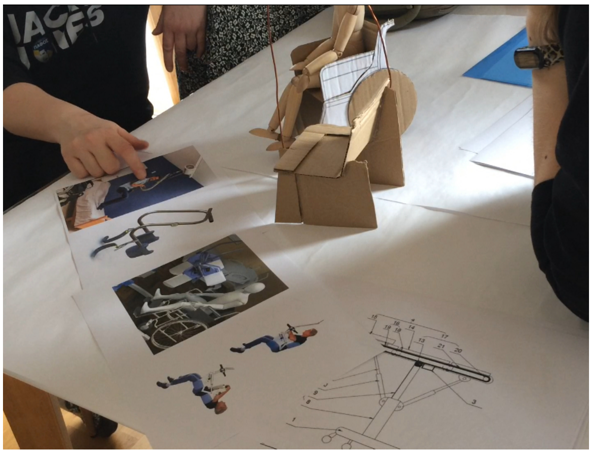


Figure 6.2: Pictures of some existing transfer aid devices and patents were used to prompt discussion

The most important topics that emerged were the following:

1. A desirable aid has to be small, compact. People with tetraplegia already have several pieces of assistive technology equipment for daily living that take up space in the home. For car transfers, the aid should fit in the trunk (and not explicitly mentioned, but obviously, should not prevent a wheelchair from fitting in the trunk at the same time).
2. A non-powered piece of equipment is preferred over one that needs charging and may turn out to be unusable because of an empty battery. This was brought up by the OT in the hospital context, but there is no reason to think it would not apply to home use.
3. Simpler user interfaces, fewer functions, and fewer pieces to assemble are in practice preferred by people over complex products – experience of the OT.
4. The participant did not put very high priority on super-light weight for a device that he would keep in the trunk of the car.

In the second part of the workshop, I pointed to the mannequin and chair models and led in with a question about the car measurements, which then led to talking about the body positioning and biomechanics of how the participant practices the transfers currently. He brought up an idea he had had for a while, which was a transfer board with a powered conveyor belt or multiple rollers as an alternative. Some aspects of the idea were discussed briefly. During a break we took from the discussion, I crafted a model of the suggested conveyor belt transfer board out of cardboard, fabric, and hot glue (figure 6.3).

The mannequin, the model wheelchair and car seat, and the freshly made transfer board model proved helpful in the communication process. The positioning of the conveyor transfer board was discussed, and it was concluded that it cannot be placed exactly the same as a normal transfer board – between the wheelchair seat and a cushion on

Figure 6.3: A model assembled during the workshop depicting the idea suggested by the participant: *conveyor belt transfer board.* Mannequin in the approximate body position for starting the transfer.

it, as the participant currently does when transferring into the car. He then suggested adding legs to one end of the transfer board to support it on the ground by the side of the wheelchair seat. Skewer legs were glued to the model transfer board, and its behavior during transfers in each direction was discussed. The OT brought up some hospital equipment that carries some resemblance and human-powered methods that are successfully used for extreme height difference transfers. The OT also noted that even though some common transfer boards are in fact quite flexible, sagging under the weight of the user is to be avoided because it would create an additional incline for the second half of the transfer and usually lead to the person sliding forward, off the transfer board.

As the central problem with the transfer was that it was going uphill and required a lift, it was accepted that the device could get power from the car cigarette lighter socket. If there was a possibility to accomplish the result without the need for power, it would be preferred, but the participants were not completely opposed to plugging a device into the car power.

Then the OT showed several methods of how transfers in general, including car transfers, can be assisted by another person, with or without a transfer board, and depending on the exact physical condition of the person transferring. The OT also explained what can typically go wrong during transfers.

Based on the clarifications received during the demo about how the participant's primary caregiver (who was not present) assists the car transfers, I proposed an idea. Currently, the caregiver stands behind the participant's back, between the wheelchair and the car's backseat door, holds on to his pants waist, and first pulls, then pushes sideways from one seat to the other. But their strength is not enough to slide uphill. The proposed idea was to involve a mechanism that would rest on the ground, be stabilized by the caregiver's weight, and also lean against the side (back door) of the car. A belt would go around the participant's waist, and a rope attachment would exert the pulling force from a point somewhere over the wheelchair's backrest. The idea was discussed briefly but did not find much support because of its size, complexity, and possible doubts about its mechanical viability.

As a final 20-minute part of the workshop, I presented three of my own prepared ideas in the form of cardboard models (figure 6.4).

"Lifting transfer board," consisting of a usual board, but additionally having an element under one end that, after placing the board, would inflate into a larger size, therefore lifting that end of the board with the person on it. The following transfer would happen on a level surface or even on a decline. The positioning of the person's body was thought through, and the sequence deemed possible.

A "longer than normal exoskeleton arm" idea received only a short discussion. This idea was inspired by something the participant had said during the interview, namely that when he tries to actively participate and help in a transfer, he feels his hands do not have enough reach.

A "harness and sliding rail" idea received a longer discussion. The OT took interest in the harness system, seeing potential for the context where the hospital receives patients who need help transferring out of the car they arrived in, but the staff has no prior knowledge of how best to do it with this particular person. None of the existing hospital patient lifts can access typical passenger cars. It was also suggested by the participant that the rail construction should reach through the car cabin instead of resting on the seat and potentially damaging it. The harness system was inspired by parachute and safety harnesses, modified for easier application onto a seated person.

Figure 6.4: Idea visualizations I had prepared beforehand and presented at the workshop: 1. *lifting transfer board, by means of an inflatable cushion*, 2. *exoskeleton arm, longer than a human arm*, 3. *harness and sliding rail*

The consensus was that two ideas were most worthy to continue work on: the *conveyor transfer board* and the *lifting transfer board*.

After this, we went to the car, and the participant and the OT demonstrated some aspects of the transfers there.

6.2 Design brief

The next phase after the co-design workshop was to build prototypes of the two concepts that were considered most worth investigating further by the consensus of the workshop participants. The objective and requirements are the same for both concept prototypes.

Objective:

- The goal of the AT to be designed is to solve a concrete problem for a concrete person with SCI and their caregiver tandem.
- The AT has to make it possible for the person with SCI to exit a sedan car and transfer to a higher wheelchair seat with the help of the caregiver who is capable of helping him on level transfers.

Requirements:

- The AT has to reduce the physical exertion required from the caregiver at least to the point where it becomes similar to what is needed for level transfers.
- The environment where the transfer takes place is typically a parking lot, outdoors.
- The AT has to fit in the car trunk, because the user does not want to modify the car.
- It has to be reasonably easy to retrieve and set up for the caregiver, and sufficiently lightweight.
- Size should not be much bigger than a simple transfer board, to allow fitting the AT and a wheelchair in the trunk of the car simultaneously.
- The car's 12 V socket can be used as an energy source if needed, because the activity for this user always takes place next to a car. If the AT is ever appropriated to another user and context, then the energy source can be reconsidered.

Deliverables are two prototypes that would be at minimum ready for testing once with the workshop participant under the supervision of the OT.

6.3 Prototyping

The lifting transfer board concept was quite straightforward. An inflatable cushion was promising to be thinner in its deflated state and of lighter weight than alternative rigid mechanical approaches, for example a scissor lift, though this is partially accomplished by displacing the bulk and the weight into a compressor that can stay on the ground or in the car.

The conveyor concept was significantly more difficult. I tried applying systematic product development methods as they are taught in textbooks like Otto et al., 2001 and Ulrich et al., 2012. Functional modeling and morphological matrix are shown in appendix 5.

I analyzed the mapped option combinations not from a commercial product perspective, but to find a viable prototyping path. The concept that had originally been described as a "conveyor belt" was modified to become a conveyor that uses rails and a sliding seat, pulled by a toothed belt, because sourcing materials for a conveyor belt, as well as keeping its weight reasonable, would have been unattainable.

The lifting transfer board prototype (figure 6.5) was made of wood, a wheelbarrow inner tube, textile materials, and a car tire compressor. Its detailed description is given in appendix 6.

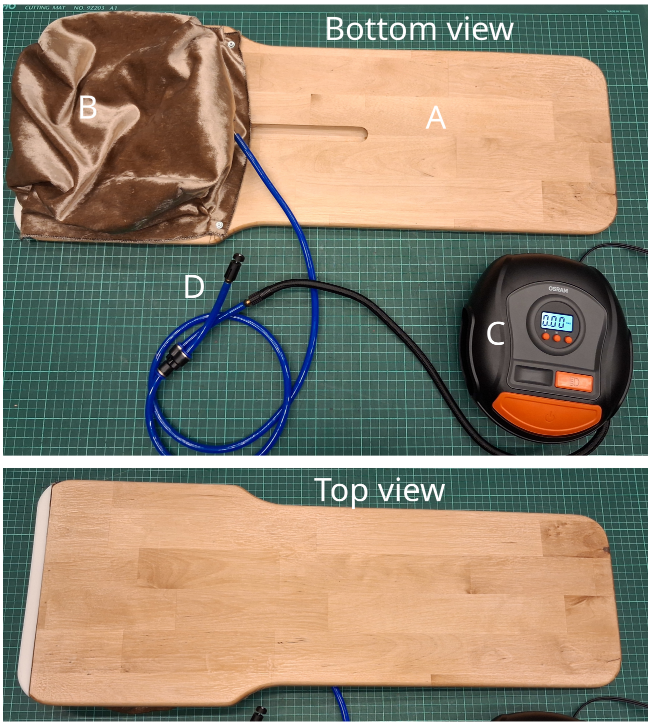


Figure 6.5: Prototype *lifting transfer board*: A – board, B – the inflatable lifting element under a velvet cover; velvet has low friction in one preferred direction and high friction in the opposite direction, C – compressor for inflating, D – valve for manual deflating.

The conveyor prototype (figure 6.6) was made of wardrobe pipes, 3D-printed parts, a battery drill motor and control electronics, an HTD-5M toothed belt, a worm drive, and old crutches. Its detailed description is given in appendix 7.

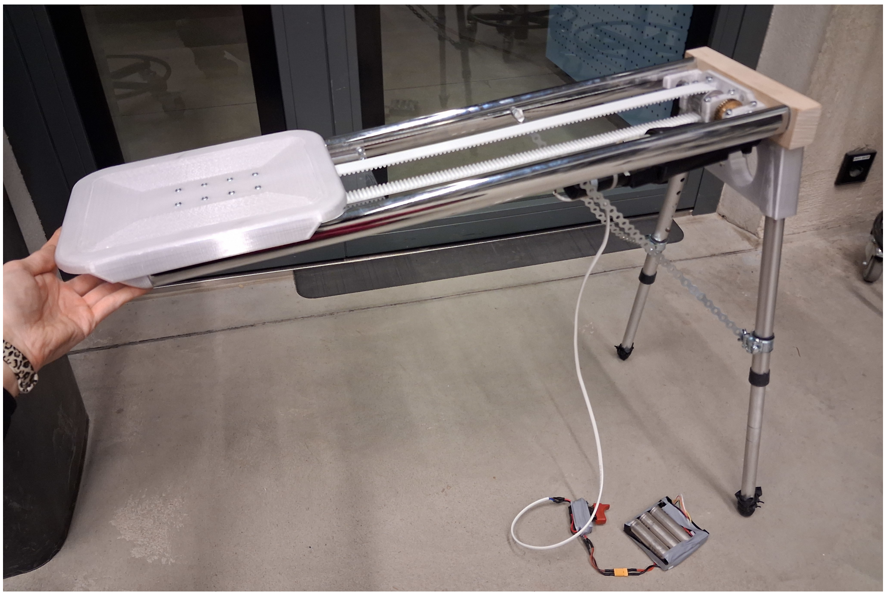


Figure 6.6: Prototype *conveyor*: a seat moving on rails, powered by a motor, with support legs on one end.

6.4 Prototype testing results

Prototype demonstration and testing were done on two occasions. First, with the participant and the OT with whom the co-design workshop had been held. During this testing, I was able to demo the lifting board once, after which it broke in a manner that was impossible to repair on the spot. The conveyor was tested by the OT. In the time between the workshop and testing, the participant had found information about an existing product that he believed would solve his problem – BeasyTrans (BeasyTrans Systems Inc, n.d.), shown in figure 5.4. In a video, it appears that the plastic-to-plastic contact has less friction than clothing-to-board contact and would make sliding easier. With that, he seemed somewhat less motivated to find out the exact functioning of the prototypes and less interested in the continuation of their development.

The OT, who saw a demo of the lifting board but was not able to test it, thought that it may be useful for car transfers in the opposite situation, where an SUV seat is higher than a wheelchair. An 8 cm lift might suffice to even out the heights for some typical cars. The OT also recommended testing the prototype with people who are doing independent or almost independent transfers.

The OT tested the conveyor prototype by moving their own body with it. The legs of the prototype are beneficial because they keep the device from slipping, but at the same time the travel ends in an awkward place in relation to the hem. Possibly attaching the legs more towards the middle could yield better results. Both ends of the conveyor should be thin; this may require special materials such as carbon fiber. The most natural position of the device seems to be perpendicular to the car body, and the wheelchair would then be placed parallel to the car, behind the conveyor device, not at an angle to the car as usual. This setup leaves more room for the assisting person in the corner between the car and car door. However, getting on the conveyor seat at the beginning is quite difficult – this is where a caregiver often struggles, because the preparation for a transfer happens in the depth of the car and caregiver needs to bend into a possibly awkward position while using their strength for the physical manipulations required.

The participant was critical of the complexity, size, and likely cost of a device that would still require a small transfer from the board to the wheelchair at the end.

In my opinion one major mechanical blind spot with the conveyor prototype turned out to be the fact that I had assumed a roughly horizontal seat, but car seat is tilted backwards significantly enough that the device did not stand in balance between its two legs and the flat opposite end. A person sitting on the device and pressing it against the car seat tilted one of the device's legs off the ground.

I also observed that inserting a 28 mm thick object consisting of several parts under a seated person is significantly more difficult than doing it with a typical transfer board that is approximately 10 mm thick, with smooth round edges and even thickness. The technique to accomplish this is for the person to lean to the other side so far that one buttock lifts from the seat. In this phase, the extra thickness is not yet a major problem. However, in the second stage, the board either has to be slippery enough to be pushed further under the person now sitting straight, or the person's body needs to be slid further onto the board. The first option is impossible on a cushioned seat with the shape of the conveyor prototype, and the second requires at least the same, if not more, force from the assisting person than sliding on a smooth incline.

I took measurements of the workshop participant's car on the testing day. The measurements were as follows: The wheelchair seat height is 56–57 cm. The car seat front edge, when not compressed by a person's weight, is also 56–57 cm from the ground. The car seat descends to a height of 48–49 cm towards the backrest. The horizontal distance between the car seat and the wheelchair in the optimal position for transferring is about 25 cm. Therefore, the height difference between the front of the car seat when sat on and the wheelchair seat when not sat on is the amount that the car seat is compressed under the person. I would estimate this to be up to 5 cm if the contact area between the person and the seat is relatively small – for example, when sitting on the edge.

The second testing took place with the supervisor of this thesis, who is living with tetraplegia, and his family member caregiver. I had repaired the lifting board and it was tested in real-life situation. I only gave a demonstration of the conveyor, because the OT testing had revealed several weaknesses and the device's stability was questionable.

Their feedback on the lifting board was as follows:

- Getting out from the depth of the car seat onto the front and side edge of the car seat, where one needs to be for this or any transfer board transfer, is still quite a challenge and requires a lot of physical effort from the caregiver.
- Once the body position on the edge of the seat is established and the board is placed, the lifting part seems to do the job, and the board works for the transfer.
- The board itself might be too narrow at the non-lifting end. When the person has already transferred onto the wheelchair, the other front corner of the seat cushion

that is not covered by the board is unstable and prevents sliding. A board reaching there could offer better balance for the body and a better sliding surface.

- The lifting cushion and transfer board might be better as two separate objects rather than one.

6.5 Conclusion

The co-design workshop held with a person who had a concrete problem with car transfers and an OT proved to be a useful tool for intensive information gathering. It created a relatively good understanding of the specifics of the problem, while already generating concept ideas and filtering the ideas I had previously come up with. To me, it seems that the workshop was also a very effective way to access the expert knowledge of the OT. I believe that in an interview format I could have missed some relevant directions, but the workshop naturally gave the OT an overview of what was needed and the freedom to bring up what they deemed important.

The only downside of the workshop was that the tangible nature of it gave an impression of good understanding of the problem and made me forget empirical data gathering – for example, the exact measurements of the car and the wheelchair. These were collected later, at the testing meeting.

Prototyping at human scale, creating something ready to test, is challenging when the purpose of the object is to move a human body, even if only by a few centimeters, but the information gathered from it is the most valuable. The conveyor prototype proved that even when the use sequence has been thought through with two experts and 3D visual aids, new aspects are discovered at full scale and with a tangible example. The limitations of available materials and technologies can leave one with a relatively weak solution. Nevertheless, it was worth testing, because in addition to our workshop, this idea has appeared in transfer AT co-creation before (Barbareschi, 2018).

The lifting board concept was significantly more straightforward to prototype and does not suffer as much from material-related limitations. I think that this concept does not yet have its final verdict after two occasions of demonstration and testing.

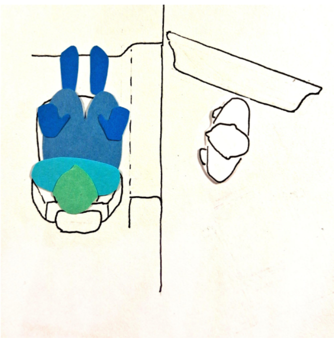
Both prototypes contributed to the discovery that, in general, one of the harder phases of car exit transfers is the start of the transfer. While during the co-design workshop the impression was that the problem lay in the incline position of the transfer board, testing on both occasions led to conversations about the fact that, as a rule, the initial part – just preparing for a transfer board transfer – is a physically challenging phase for the caregiver.

Figures 6.7 and 6.8 show the sequence of a transfer from a car to a wheelchair. Getting from the starting point, the normal car-seated position (figure 6.7, state 1), to sitting on the side and front edge of the seat, with feet outside on the ground (figure 6.7, state 2), is quite elaborate and difficult. This is where, as a rule, assistance is needed for the following reasons:

- The car seat has an incline from back to front and on the side edges. The car seat is designed to resist a passenger sliding sideways in the event of a car crash. The forward incline is likely intended for a comfortable seating position and to prevent sliding during sudden braking when the seat belt does not lock. Essentially, the car seat is designed to resist the motion that is required here.

- Without the use of trunk and leg muscles, it is extremely difficult to slide oneself forward, even with the presence of a backrest.
- If the sliding leaves the trunk leaning on the backrest, then bringing it upright again without the use of abdominal muscles would require something to hold onto and pull, but the car interior does not provide ways to do this without finger grasping, which is also impossible for someone with tetraplegia.
- Legs have to be lifted over the car's door frame, which may be approximately 10 cm higher than the car floor and about 20–25 cm wide. Paralyzed legs can only be moved by someone lifting them manually. The distance to the outside ground is long enough that moving the legs needs to be done in multiple smaller steps, alternating with moving the hips on the seat. This is something that the caregiver can do more effectively than the person with tetraplegia themselves.
- The space around the car seat is limited, and the car roof can make access more difficult for the caregiver. The car door, in its open position, also limits the available space. The caregiver cannot position themselves in a way that would be most natural for similar pulling and lifting motions if there were no obstacles.

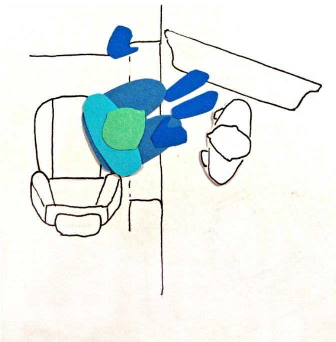
1



Feet, thighs, torso, head and hands are shown, arms and lower legs are not.

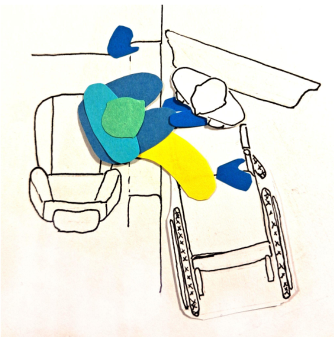
A person is seated in a normal position on a car seat: centered and all the way back towards the backrest.

2



First the person has to slide forward on the seat and towards the door side edge of the seat - the seat is inclined in both of these directions. And at the same time both feet have to be moved out onto the ground. This may need assistance.

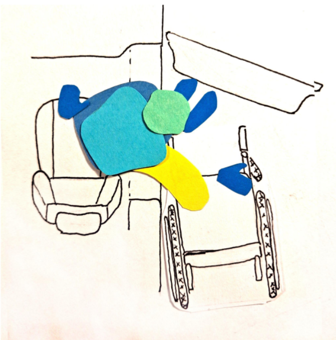
3



Wheelchair is placed in a position close to the car, by the assisting person. Wheelchair footrests, if movable, are set out of the way. Transfer board (yellow) is placed under the person and his seating position adjusted.

Following steps are shown without the assisting person for picture clarity, but in many cases the assisting person is still standing in the narrow space between the car and the car door and also needs to bend down to reach the pants waist of the transferring person.

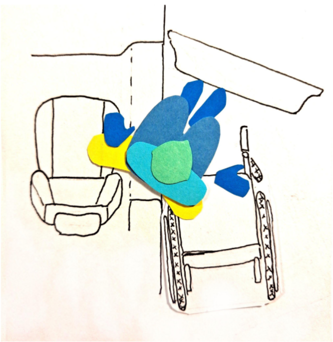
4



To start an independent transfer or to contribute in assisted transfer the person supports trailing hand on the car seat close to their hips and leading hand on wheelchair or on transfer board, further away from the body. He leans his torso forwards in a swift move. This will carry bodyweight onto the legs and straightened arms and lift the buttocks a little bit up. Accompanied with sideways push and pull with the arms, he will land back sitting closer to the leading arm.
If the person can't contribute as much, he may just use his arms to stabilize his torso while the assisting person creates the lifting and sideways force holding form his pants waist. Bending forward is necessary so much that the head would not get stuck under the upper doorjamb.

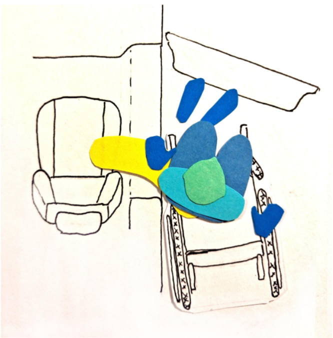
Figure 6.7: Sequence of a typical transfer from a car to a wheelchair performed by someone with C5–C7 tetraplegia. Continues in figure 6.8.

5

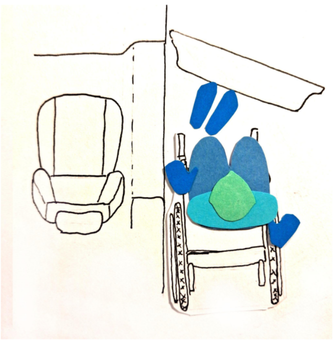


The person has moved forward on the transfer board. Positioning of the hands is adjusted and the process of swift forward bend of the torso causing the buttocks to lift and sideways push-pull with arms is repeated as many times as needed.

6

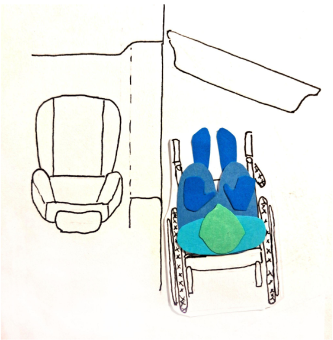


7



The transfer board is removed, but the person is sitting on the front edge of the wheelchair seat and their legs are still on the ground.

8



Seating position is adjusted by centering and moving further towards the backrest on the seat and footrests are put to normal position and legs placed on footrests. This may also need assistance.

Figure 6.8: Sequence of a typical transfer from a car to a wheelchair performed by someone with C5–C7 tetraplegia. Continued.

7 DESIGN CONCEPT PROPOSAL

Based on the observations from prototype testing, the objective for the final concept was adjusted. The design solution (figure 7.1) is meant to reduce the physical burden on the person with tetraplegia and caregiver tandem on transfer from a sedan car to a wheelchair by temporarily reshaping the car seat into a level surface (figure 7.2). This facilitates sliding the seated person more easily than the valley-shaped car seat itself. A few centimeters of lift also occur, which can reduce or negate an incline toward the wheelchair and ease a transfer-board transfer - thus adressing the problem that the co-design workshop participant had.

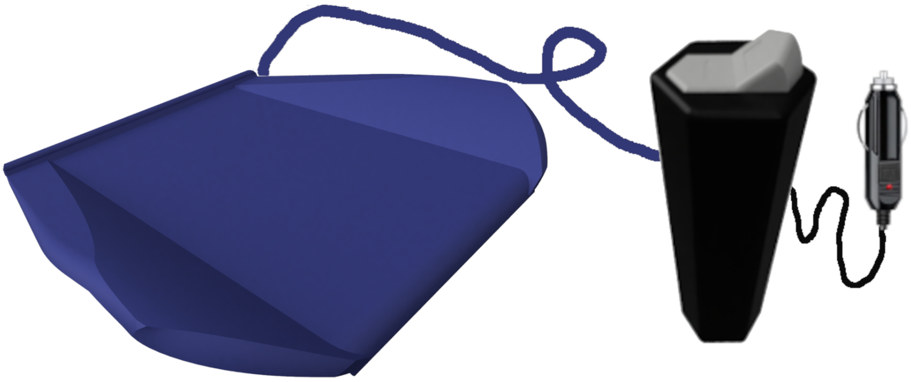


Figure 7.1: Product parts left to right: inflatable working element "pillow" (with a textile cover not shown in the image), an enclosure with control buttons containing a pump and optionally a battery, and 12 V power plug for car use. (CAD drawing made and rendered with Autodesk Fusion)

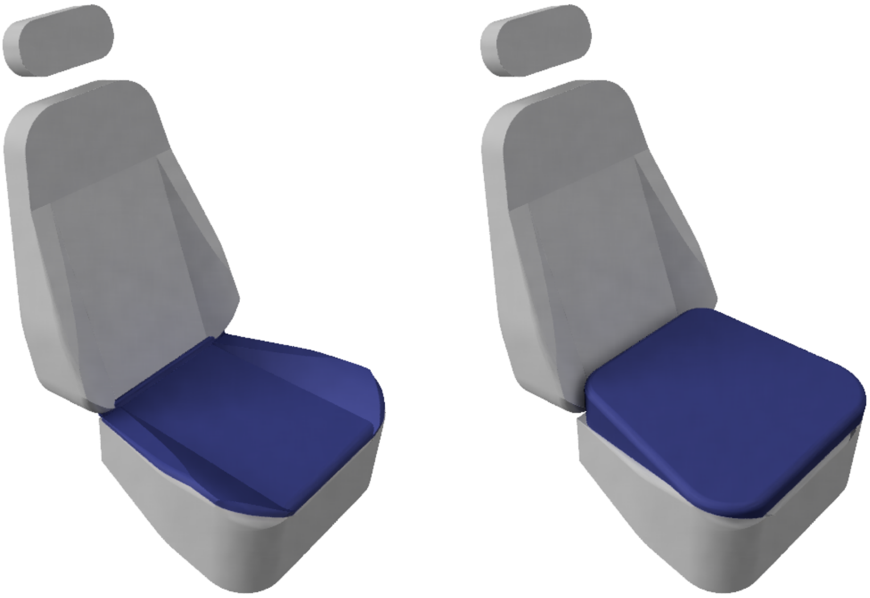


Figure 7.2: Lifting pillow in deflated and inflated states. (CAD drawing made and rendered with Autodesk Fusion)

The central element of the product is an inflatable pillow that, when inflated, takes the shape of the negative space that exists between a car seat's sitting surface and a horizontal plane a few centimeters above it. When deflated, the product should be as thin and flexible as reasonably possible to preserve the ergonomic properties of the car seat. The pillow is inflated to a pressure that makes it sufficiently rigid so that a person seated on a small area (15 cm × 30 cm) on its edge does not deform the pillow significantly.

The pillow can be inflated with a compressor housed in a unit that can be placed in a cup holder, on the floor of the car, or hung. In addition to the compressor, the housing also contains an impeller that allows the pillow to be fully deflated without the need to press down on it. The compressor/impeller can be powered either from a 12V car cigarette lighter socket or from a Li-Ion battery pack. The battery pack, in turn, can be charged either from the car socket or with an indoor wall charger. This is to facilitate flexible use: even though the primary use case for the product is a motor vehicle seat, some people might use it in their own vehicle where the 12V socket is available and reliable, while others may use it in various vehicles where socket availability is unknown— or for mixed-use cases.

The pillow could be made with dropstitch technology (figure 7.3), which allows the production of inflatable objects that have an almost flat surface, as opposed to the bulging sections of, for example, more traditional air mattresses. Dropstitch allows achieving significant stiffness at relatively low pressure. This technology is used, for example, in making inflatable stand-up paddling (SUP) boards. A special textile is woven that consists of two layers of dense fabric and threads that connect them together at regular intervals. The length of these loose threads determines the thickness of the product in its inflated form. The fabric layers are then covered with PVC or a similar material on the outside, which makes them airtight. To make the two interconnected layers into an inflatable product, the desired shape is cut out, the open edges are brought close to each other, and a PVC strip is glued over them.

Figure 7.3: Dropstitch material sample (Halswell et al., 2012)

So far, the industry is relying on dropstitch materials of uniform thickness (Haining Duletai New Material Co, n.d.). This application requires thickness variation according to the seat shape (see figure 7.4). I suggest producing a variable-thickness dropstitch-like fabric assembly in such a way that fabric pieces are prepared with a little extra allowance, then attached to frames that keep them in the desired position. A long needle is then used to hand-stitch or machine chain-stitch them at approximately regular intervals. The outer surfaces are then covered in PVC sheets, and the edges are connected similarly to the SUP board production method.

The exact geometry of the pillow assembly needs detailed investigation and experimen-

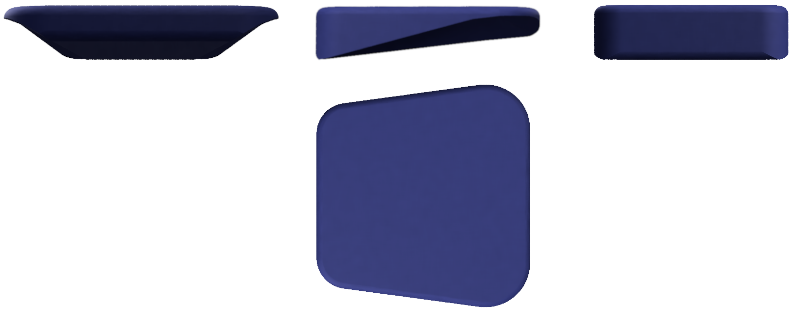


Figure 7.4: Lifting pillow shape (CAD drawing made and rendered with Autodesk Fusion, rendering with perspective)

tation: to determine the behavior of connecting ties of varying length and to find a pattern that, in the deflated form, ensures the vertical section of the front edge folds downward to prevent it from pressing on the back of a person's knees.

As the fabric and PVC layers inevitably make the seat surface stiffer, a textile cover with thin batting is added to restore softness. Additionally, a textile or faux leather cover might extend the lifespan of the product by protecting it against UV aging and friction wear. As a bonus, the cover also reduces the unwanted effects if a PVC repair patch is ever needed.

The product will be repairable. PVC SUP boards are repairable (NRS, n.d.), and doing so does not require specialized tools or a rare skill set. The textile cover has to be removable to allow repair, but must attach securely during normal use. Ideally, the cover should be a simple enough construction to be remade by someone with average sewing skills. The air hose between the compressor and the pillow must be a standard, widely available tube and replaceable with common tools. The battery pack should allow for replacing the battery cells at the end of their life cycle by a qualified professional, in a manner that is easily discoverable and quick to execute.

PVC is not considered an environmentally friendly material in applications where viable alternatives exist (Kudzin et al., 2023). The composite material of this product currently makes it non-recyclable. However, the repairability and durability of PVC promise a long product lifespan, and we can assume that the need for such a product is not short term for the potential consumer.

In addition to the target group with whom the study was conducted, such a product could benefit paraplegic individuals who do not possess high levels of upper-body strength, such as older adults and women. The number of older adults with SCI is increasing due to population aging (Kim et al., 2025). The product may also serve wheelchair users with various health conditions, or older adults who experience mobility difficulties and find it challenging to move from a seated position in a car to the edge of the seat where they can rise to their feet.

In a small proportion of cases, this product may facilitate executional independence for people who can drive but face a minor barrier when exiting the car. However, the primary impact is more likely to lie in tipping the balance in situations where individuals do not participate in activities outside the home because family members or friends who could drive them face a physical challenge that slightly exceeds their capabilities during car exit. In such circumstances, people may undertake a trip in an emergency, willing to seek outside help, but feel reluctant to ask for assistance for activities related to entertainment or socializing.

The product may also serve to sustain the health of caregivers who perform transfers regardless, but who exceed a level of physical exertion that is sustainable in the long term.

The physical product alone may not be sufficient. A guide on how to assist a person in transferring between a car and a wheelchair, or from a car to standing, should accompany the product. Such information exists scattered across the internet, at least in the English language, but in most cases family members of people who need assistance with car transfers are improvising. For effective and safe use, a well-designed guide, available in multiple modalities and local languages, must be easy to access.

Secondly, this type of product must be tested in context for each potential user to determine whether it adequately addresses their problem. Therefore, a sales model that allows testing before committing to purchase should be available.

8 CONCLUSION AND DISCUSSION

The research questions, in brief, received the following answers:

1. What are the key physical, social, and personal factors shaping the experience of wheelchair transfer for people with C5–C7 level tetraplegia? The interviews showed that people with tetraplegia perform a low number of wheelchair transfers per day, and the most common transfers inside the home are sufficiently streamlined – whether done independently or with the help of family member caretakers. Car transfers, on the other hand, tend to require assistance every time, either from a family member or another person found on the spot – sometimes both, when the physical challenge exceeds the family member's capabilities.

Attitudes toward transfer assistive technology (AT) are complex. Factors that influence the decision to purchase and use a specific AT device include the following: Does it take up too much space at home? Does it make my home look less aesthetically pleasing and more medicalized – less normal? Does using the AT help sustain the health of my caregivers? Does not using the AT give me physical exercise and sustain my own health? Could I manage without it and be less dependent on AT? Is it affordable?

2. What priorities and requirements from the perspectives of people with tetraplegia and caregivers emerge from co-design activities within a design-for-one context? The design-for-one approach enabled sharp focus on one specific problem, described in terms of the incline transfer from car seat to wheelchair and the challenge it poses for the assisting person. The co-design meeting reinforced the understanding that large and visibly disability-related objects are disliked.

3. What does iterative prototyping contribute to the understanding that verbal and visual communication alone does not reveal? Although an idea was analyzed during the co-design workshop in the presence of two experts – the problem owner and an occupational therapist (OT) – and supported with cardboard models and a doll, prototype testing later revealed that important details were still missing. The doll and models were helpful, but they are not sufficient when dealing with the complex task of moving a human body in a constrained environment.

Prototype testing revealed a pattern in car transfers: that the initial phase – when the person must move from a normal seated position in the car to sitting on the edge of the seat with feet on the ground outside – is often a challenge and a burden for caregivers. This had not come up in interviews or during the co-design workshop discussions. It is likely that this discovery could have been made through extensive observation, but the prototypes offered additional insight into what does not work.

Personal reflections. The OT's presence during the co-design process and testing helped ensure that no harm would result from overly daring experiments. At the same time, it allowed me to avoid self-censoring ideas out of fear of causing harm – because all ideas would be filtered through an expert.

The authors of the “Design for (every)one” framework argue that, in iterative prototyping of AT, there should be a constant back and forth between the questions “What is needed?” and “What can be built?” (De Couvreur et al., 2011b). This resonates with the challenges I faced while building the conveyor prototype under resource-limited conditions. The prototype was not close enough to the initial idea to definitively prove it a dead end, even though the result was no match for the problem.

The lifting board prototype did not suffer from such a noticeable divide between the aim and the means, except for the unfortunate breakdown that hindered testing. This is one chicken-and-egg problem: it would be smart to do stress testing before human testing, to avoid such failures, but overly vigorous stress testing – and possible repairs it may require – demands resources that could be wasted if human testing later reveals the concept is not viable.

Positioning of the concept proposal. The proposed concept moves into a technologically uncertain area; the production method for the product has yet to be engineered and verified, though I have initial ideas about it.

Before prototyping the production method, however, some user testing should be conducted. A styrofoam mock-up of an inflated pillow in a realistic cover textile would allow verification that the transfer from the top of the pillow does in fact require less physical effort than a default car transfer. Such testing could also reveal unexpected side effects that need to be addressed. Unfortunately, further prototyping did not fit into the scope or timeframe of this thesis.

SUMMARY

Spinal cord injuries are a health condition that has multitude of negative effects on the life of the person suffering it. Everyday tasks can pose significant barriers unless intentional effort is made by the society to make built environments, including residential housing, accessible. A person with a spinal cord injury is in most cases going to be a wheelchair user, and one difficulty faced, is getting into and out from the wheelchair. The small number of people with tetraplegia interviewed for this thesis, had the wheelchair transfers in their home environment streamlined, be it with assistive technology, physical training, or help of family members. Car transfers pose more problems, people with tetraplegia tend to use cars with someone, a family member or a taxi driver, and they need assistance for getting from wheelchair to car seat and back again later.

Design has to address situations where access to basic transportation means is hindered, because a family member does not possess sufficient strength to help the person with SCI, or when a family member might be hurting their own health in doing it despite the hardship.

This thesis project took design-for-one approach, recommended by several authors for designing assistive technologies. A co-design workshop was held with a person with SCI resulting in tetraplegia and an occupational therapist – a professional who advises people with disabilities about the strategies that enable activities of daily living with physical limitations and about the appropriate assistive technologies available. The workshop participant's concrete problem was targeted by the design attempt: he and his family member caregiver face a need to find additional help every time he has to transfer from his car to wheelchair.

Two ideas from the workshop were built into full size and functional prototypes. Both of them aimed to use electrical energy to reduce the demand posed by an incline height difference on the caregiver when assisting the wheelchair transfer. The prototypes testing led to a new insight, that it is common for the caregivers to struggle in the first phase of car-to-wheelchair transfer, when helping a person with SCI to get from a normal seated position to the edge of the car seat, feet on the ground outside.

The design proposal part of this thesis addresses that common problem and also the height difference problem faced by the co-design workshop participant. The proposed assistive technology solution is an inflatable ”pillow” that rests on a car seat in deflated state during the ride. But once a transfer out from the car needs to be performed, the pillow gets inflated into a shape that makes the normally valley shaped car seat, that is meant to prevent the passenger from sliding forward and sideways, into a raised and fully horizontal surface that facilitates sliding the seated person in any necessary direction.

This kind of product of course will not offer an all-encompassing solution, but it might tip the balance in situations where a person with tetraplegia or paraplegia or other health condition is only transported by car in emergency situations, when the act of asking help from strangers is accepted better. If the family or friends can handle the necessary assistance on the car transfers, there are more opportunities to socialize and participate in activities outside from home for the person with mobility limitations.

KOKKUVÕTE

Seljaaju vigastused on terviseprobleem, millel on selle kannataja elule palju negatiivseid mõjusid. Igapäevased toimingud võivad olla märkimisväärselt takistatud, kui ühiskond ei tee teadlikke pingutusi, et muuta ehitatud keskkond, sealhulgas elamud, ligipääsetavaks. Seljaaju vigastusega inimene on enamasti ratastoolikasutaja ja üks raskus, millega kokku puutub, on ratastooli siirdumine - enese liigutamine muult pinnalt ratastooli või vastupidi sealt välja. Nende väikese hulga tetrapleegiaga inimeste jaoks, keda selle magistritöö jaoks intervjueerisin, olid ratastooli siirdumised kodus küllaltki hästi lahendatud, kas abistava tehnoloogia, enda füüsilise treeningu või pereliikmete abiga. Auto ja ratastooli vahel siirdumine aga osutub keerulisemaks. Tetrapleegiaga inimesed tavaliselt kasutavad autot koos kellegagi, pereliikme või taksojuhiga, ning nad vajavad abi ratastoolist auto istmele ja tagasi siirdumiseks.

Disain peab tegelema olukordadega, kus juurdepääs tavapärasele transpordivahendile on takistatud, kuna pereliikmel pole piisavalt jõudu, et aidata seljaaju vigastusega inimest, või kui pereliige abistab kõigest hoolimata ja paneb sellega ohtu enda tervise. Selles magistritöös kasutasin disain-ühele lähenemist, mida mitmed autorid abistavate tehnoloogiate disainimisel soovitavad kasutada. Üks osa protsessist oli koosloome töötuba, kus osales seljaajukahjustusega inimene, kellel on selle tulemusena tetrapleegia, ja tegevusterapeut – spetsialist, kes nõustab puuetega inimesi selles, kuidas füüsiliste piirangute tingimustes igapäevase elu tegevustega siiski toime tulla ning sobivate abivahentide osas. Disainiga võtsime sihikule töötoas osaleja konkreetse probleemi: tema ja tema pereliikmest abistaja peavad leidma appi veel mõne tugevama inimese iga kord, kui ta autost ratastooli siirdub.

Töötoa kaks ideed said prototüübitud täissuuruses ja funktsionaalsena. Mõlema kontseptsiooni tuumaks oli elektrienergia abiga vähendada koormust, mis langeb abistajale, kui siirdumine toimub madalamalt autoistmelt kõrgemasse ratastooli.

Prototüüpide testimine viis uue arusaamani, et küllakti tihti on abistajatel autost ratastooli siirdumise kõige esimeses etapis enim raskusi. Nimelt siis, kui seljaajuvigastusega inimene peab tavalisest istumisasendist autos saama istme välisserva peale nõnda, et jalad on õues maas.

Selle lõputöö disainiettepaneku osa käsitleb seda levinud probleemi ja ka kõrguse erinevuse probleemi, millega koosloome töötoa osaleja silmitsi seisab. Kavandatud abistava tehnoloogia lahendus on täispumbatav ”padi”, mis sõidu ajal on õhukese kihina autoistme peal. Siis, kui on aeg autost välja tulla, pumbatakse padi kompressori abil õhku täis, mis muudab autoistme, mille omaduseks on muidu takistada reisija libisemist ette ja küljele, horisontaalseks pinnaks, ning võimaldab istuva inimese libistamist vabamalt igas vajalikus suunas. Selline toode ei paku muidugi kõikehõlmavat lahendust, kuid see võib kaalukeelt nihutada olukordades, kus tetrapleegia või parapleegia või muu terviseprobleemiga inimest transporditakse autoga ainult hädaolukordades, kus võõrastelt abi palumist ei peljata. Kui perekond või sõbrad saavad auto siirdumisel vajaliku abistamisega hakkama, on liikumispuudega inimesel rohkem võimalusi väljaspool kodu tegevustes osaleda ja suhelda.

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A APPENDICES

Appendix 1: Interview questionnaire (translation)

1. How long ago did your spinal cord injury occur? How old were you then?
2. Do you live alone or with family members?
3. What do your typical days look like? What activities do you do on a weekly basis?
4. What means of transportation do you use outside your home?
5. How do you get around your home (apartment, house, garden)?
6. What aids do you use in your daily life to get around and get things done?
7. Does anyone help you with your daily chores? What are some routine activities that someone always helps you with?
8. Please tell me about a time when you had to ask strangers for help, that you think is a typical way things go.
9. Tell me the story of your wheelchair(s) (current and previous). For what reasons did you have to replace your previous wheelchair(s)? What are the pros and cons of your current one(s)?
10. What mobility aids would you ideally like to have on hand? For both indoor and outdoor mobility.
11. What activities do you miss the most that you could do before your injury or that you see other people doing, but you don't have the opportunity?
12. What daily activities take up an inordinate amount of time? Why?
13. Do you feel that your family members are missing out on something (activities and experiences) in life due to your spinal cord injury?
14. Are there any incidents, little nasty things that happen because of the condition of your legs and hands, that ruin your mood for the whole day or are hard to accept?
15. Do you remember any bright moments after learning to live with a spinal cord injury that made you feel that everything was not as bad as it seemed before?
16. What skills have you learned since your injury that have had the most positive impact on your self-esteem?
17. How many times a day do you transfer between your wheelchair and other places? Please describe typical transfer process step by step.
18. How does transferring affect your health and well-being? (Both positive and negative effects.)
19. Do you sometimes skip activities or do things differently to avoid transferring?
20. Are there any dangers in your home environment - something that could happen and have bad consequences? Like falling out of your wheelchair or something else.

21. How do you imagine your life in 10 years? What thoughts do you have about yourself getting older? What do you hope for the future? (E.g. changes in society and developments in medicine and technology.)

22. If you receive assistance every day: do any activities, when and how to do them, sometimes cause conflict with the person assisting you?

23. How often do you go out of the house to meet people or do something together?

24. If you could use a robot or a lift or perhaps a smaller assistive device to help you transfer between your wheelchair and other places, what would you consider to decide whether you want to use this device or not? Circumstances that concern yourself, your home environment, features of the assistive device.

25. Have you ever improvised a solution to a problem related to mobility or manual activity?

26. Have you found a solution to a problem in collaboration with an occupational therapist, where you used some objects or materials that were not ready-made assistive devices?

27. Do you have any other thoughts about your mobility and transferring that you would like me to know when I try to invent an assistive device?

Appendix 2: Informed consent form for interview participants (translation)

Dear participant,

I am conducting this interview as part of my master's thesis in the Design and Technology Futures curriculum, which is a joint curriculum of Tallinn University of Technology and the Estonian Academy of Arts. The aim of the work is to design an assistive device for a person with a spinal cord injury - the exact purpose of the assistive device will be clarified during the work. Through the interviews, I will try to understand the context of the daily life of people with a spinal cord injury, for the end goal of creating some innovative solution that would support independence.

If you do not wish to answer some of the questions, just say so. You do not need to justify your wish.

I ask for your permission to record this interview. I will only use the recording to transcribe it, after which I will delete the recording. No one except me will have access to the transcription in its entirety. I will destroy the transcription after the thesis has been defended.

In the written part of the master's thesis, I will use the information I received from you, together with that received from the other interviewees, to analyze and draw conclusions. To illustrate some of the conclusions, I may include a short quote in the paper along with the speaker's gender and approximate age (for example, ”woman, in her forties”). In the paper, I list information about the participants: gender, approximate age, whether they live alone or with family members.

I will keep your participation in the study confidential. I will keep this consent form with your name only in case legitimate authorities wish to verify my work was conducted ethically. I will destroy the consent forms after 3 years. The master's thesis (in English, with an Estonian summary) will be published in the Tallinn University of Technology digital repository (https://digikogu.taltech.ee) after successful defense.

Participation is voluntary for you. If you feel that you wish to withdraw your consent, you can do so at any time during the interview or afterwards until April 24, 2025 by informing me of this wish verbally or in writing (anna.jogi@taltech.ee). You do not need to provide a reason for withdrawal. If you have any questions about anything related to the study or the interview, please feel free to ask.

Gratefully, Anna Jõgi

—

I voluntarily agree to participate in the study described above, under the conditions as described. I have been informed about the purpose of the study, the use of the data and have been able to ask my questions. I understand that I can withdraw my consent or stop the interview if I wish.

Name:	Interviewer and responsible person:
Signature:	Anna Jõgi
Date:	Signature:

Appendix 3: Consent form for workshop participants (translation)

Dear participant, I am conducting this workshop meeting as part of my master's thesis in the Future of Design and Technology curriculum, which is a joint curriculum of Tallinn University of Technology and the Estonian Academy of Arts. The aim of my master's thesis is the design of an assistive device, and the content of the workshop is co-creation.

In the workshop, I would like to implement cooperation between three parties:

- the client, or the person for whom we are creating the assistive device – an expert in their own needs and abilities;
- an occupational therapist – a specialist of creating adaptations and of safety, who understands the client's abilities and needs in a multifaceted way;
- a designer/engineer – my role is to introduce and combine the possibilities offered by technology that can be used to solve the problem, and to lead the discussion.

I ask for your permission to record our meeting as video and audio. I will only watch and listen to the recordings in order to write a summary of how the activity went in my master's thesis. No one else will have access to the recordings. I will delete the recordings after defending the master's thesis.

If during the meeting there is a moment that I would like to illustrate in the master's thesis with a frame from a video where you can be seen, I will contact you later to ask for permission to use a specific image (if desired, with face blurring or other image processing that suits you).

I will keep your participation in the study confidential. I will keep this consent form with your name only in case legitimate authorities wish to verify that my work was conducted ethically. I will destroy the consent forms after 3 years.

The master's thesis (in English, with an Estonian summary) will be published in the Tallinn University of Technology digital repository (https://digikogu.taltech.ee) after successful defense.

Participation is voluntary for you. If you feel that you wish to withdraw your consent, you can do so at any time during the meeting or afterwards until April 24, 2025 by informing me of this wish verbally or in writing (anna.jogi@taltech.ee). You do not need to provide a reason for withdrawal. If you have any questions about anything related to the study or today's workshop, please feel free to ask.

Gratefully, Anna Jõgi

—

I voluntarily agree to participate in the study described above, under the conditions as described. I have been informed about the purpose of the study, the use of the data and have been able to ask my questions. I understand that I can withdraw my consent or stop participation if I wish.

Name:
Signature:
Date:

Organizer and responsible person:
Anna Jõgi
Signature:

Appendix 4: Consent form for prototype testing participant (translation)

Dear participant, The purpose of this meeting is to test and/or receive comments on two prototypes that have been built as part of my master’s thesis in the Design and Technology Futures, a joint curriculum of Tallinn University of Technology and the Estonian Academy of Arts. The purpose of my master’s thesis is the design of a transfer aid.

At this meeting, I would like to find out how the solutions built as prototypes work, what their shortcomings and strengths are, and whether they generate ideas for further developments.

I would like to ask for your permission to record our meeting. I would like to make an audio recording of the entire conversation and occasionally take photos or video of some of the testing. No one but me will have access to these recordings. I will use them for writing down the important points of your feedback truthfully.

If any image or frame in the video proves valuable as a possible illustration in the written part of the master’s thesis, I will contact you to ask for separate permission to use the specific image (if desired, with face blurring or other image processing that suits you). I will not publish any image without the explicit permission of the person(s) in the image.

I will keep your participation in the study confidential. I will retain this consent form with your name only in case legitimate authorities wish to verify the ethics of my work. I will destroy the consent forms after 3 years.

The master’s thesis (in English, with an Estonian summary) will be published in the Tallinn University of Technology digital collection (https://digikogu.taltech.ee) after successful defense.

Participation is voluntary for you. If you feel that you would like to withdraw your consent and participation, you can do so at any time during the meeting or afterwards until December 30, 2025 by notifying me of this wish verbally or in writing (anna.jogi@taltech.ee). You do not need to provide a reason for withdrawal. If you have any questions about anything related to the study or today’s meeting, please feel free to ask.

Gratefully, Anna Jõgi

—

I voluntarily agree to participate in the study described above, under the conditions as described. I have been informed about the purpose of the study, the use of the data and have been able to ask my questions. I understand that I can withdraw my consent or stop participation if I wish.

Name:	Organizer and responsible person:
Signature:	Anna Jõgi
Date:	Signature:

Appendix 5: Engineering concept development for conveyor

For the more complex conveyor belt idea I tried applying systematic product development methods as they are taught in textbooks like Otto et al., 2001 and Ulrich et al., 2012.

Functional modeling. Product function is a relation between available inputs and desired outputs (Otto et al., 2001). I defined the function as: *Support user's body as a seating surface and provide powered move towards the destination seat.*

Function diagram describes the energy, material and signal inputs and outputs of the system and explores the inner functions without referring to concrete means of accomplishing them. Figure A.1 is function diagram for conveyor transfer board.

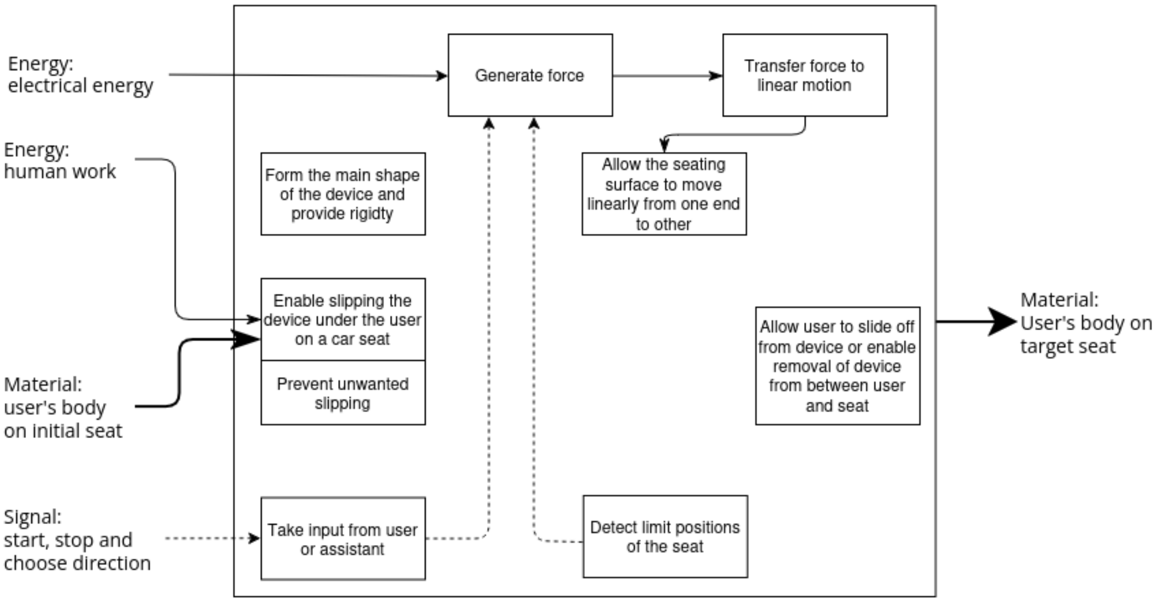

Figure A.1: Function diagram of ”conveyor” concept

Morphological matrix. Morphological matrix is made by mapping various technological means for fulfilling each function separately. It can then be used for selecting combinations and developing concepts around them for later comparison. Figure A.2 shows the options I came up with for conveyor.

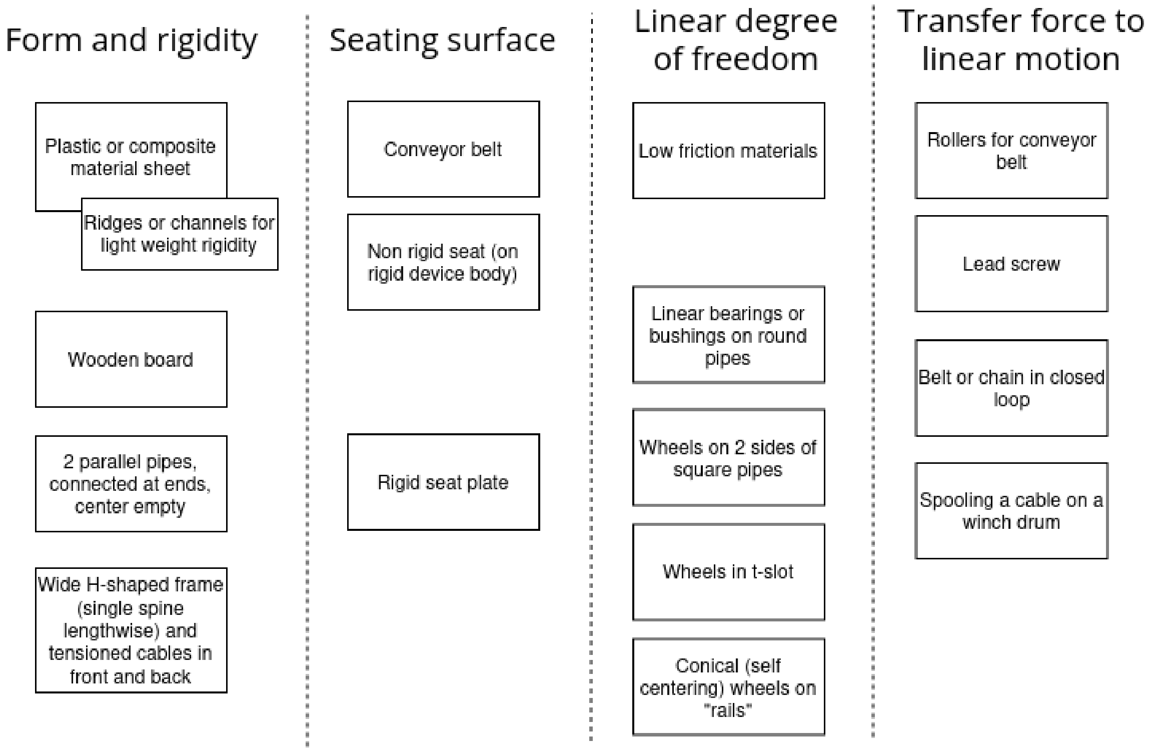

Figure A.2: Morphological matrix for ”conveyor” concept

I analyzed the mapped options combinations not from a commercial product perspective, but for finding viable prototyping path.

Original conveyor belt idea had to be discarded because first I didn’t know where to acquire material that would 1. withstand the necessary forces without stretching, 2. have sufficiently low friction in contact with viable plate material, 3. allow sufficiently higher friction to some roller material to be pulled by motor without slipping. For prototyping I chose: two parallel pipes for rigidity and sliding surface with rigid seat plate as the only fit for the pipes; PTFE elements as facilitators for sliding; closed loop toothed belt, because of it’s commercial availability. Additionally the belt made it easier to place a motor within a smaller device perimeter compared to a ordinary conveyor belt.

Appendix 6: Description of prototype ”Lifting transfer board”

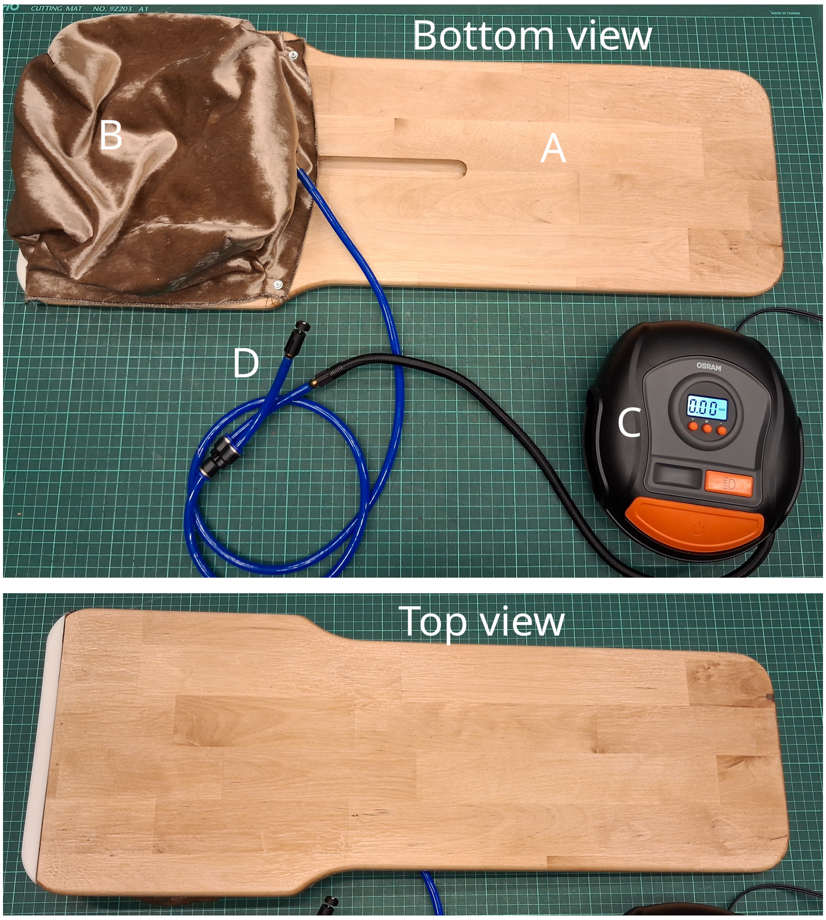

Figure A.3: Prototype *lifting transfer board* overview

The overall size of the device is 716 mm * 280 mm.

The main body of the prototype (figure A.3 A) is made of glued laminated timber, 18 mm thick. The ends of the board decrease in thickness, down to 10 mm. There are grooves in the underside to to accommodate plywood parts that hold the textiles without increasing the board thickness. The board shape was 3D modeled with Autodesk Fusion CAD software and manufactured using a CNC milling machine. The surface was sanded, finished with furniture varnish and sanded lightly again to acquire slippery surface.

The working moving part (figure A.3 B) of the device is a wheelbarrow inner tube (figure A.4 B) (size marking 3.50-4/4.00-4/4.10-4) that has been modified. The original Schrader valve has been cut off. A hole has been made on the opposite, outer side of the toroid shape and a Presta valve cut from a bicycle inner tube has been glued there with vulcanizing glue. The hole left by the original valve has been patched up. Two pieces of plywood, one with a hole to accommodate the valve, were used as a clamping jig to press both glue joints (one at a time).

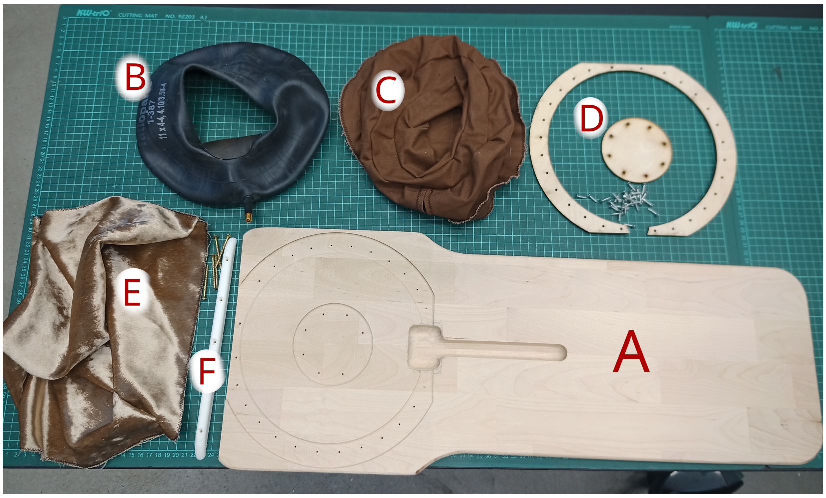

Figure A.4: Subset of components of prototype

The inner tube is covered with a woven (not prone to stretch) textile ”hat” (figure A.4 C) that limits how large it can expand when inflated, because inner tubes can burst when stretched over a reasonable size. Additionally it provides support to the glue joints of the two inner tube patches. The hat is attached to the board on the outside perimeter and inside the toroid with 3 mm thick plywood shapes (figure A.4D), made with a laser cutter, that have an array of 12 mm long screws holding them.

To facilitate inserting the device on a car seat, partially under the buttocks of a person, the rough textile ”hat” has been covered with a sleeve made of furniture velvet (figure A.4 E). Velvet's directional pile allows slippery effect in one direction and works against it in the opposite direction. This is useful when a sliding transfer is done starting from the lifting end. When the assistant pulls the person's body forward, there is inevitably some friction catching on to the board and board sees the effect of being pulled away for the initial seat, which can lead to a fall. Velvet will prevent this from happening when in contact with a textile car seat. When doing the transfer in the opposite direction, the effect is not favorable, the board could slip further on the second seat and drop off the first seat. But this is unlikely to happen in the intended use case, where for entering the car the board would be used without the lifting feature, using a decline transfer. For such case, to facilitate removing the board from under the person afterwards, it is better to start from the end with the velvet, because the simple wooden end is easier to slide out afterwards.

The velvet sleeve has to be held strongly to the main body of the board in it's end. This is accomplished by squeezing the textile between the board and a 3D printed slat (figure A.4 F), held by 5 screws, additionally reinforced with a metal wire in a tunnel sewn in the textile.

The Presta valve's inner parts are removed from the valve attached to the wheelbarrow inner tube, because deflating the tyre has to happen in a more accessible location of the device. Silicone tubing meant for compressed air (OD 8 mm, ID 5 mm) is attached to the Presta valve casing (OD 6 mm). The tube goes to a 3-directional fitting. Second run of the tube from the fitting has a Schrader valve for attaching an air compressor (tyreless tube valve with rubber layer removed yielded an approximate OD 5mm). The third run (figure A.3 D) has another Schrader valve with 3D printed ”button” the function of which is to enable deflating the system. Deflation requires pressing the working element flat at the same time as the button is held.

A commercially available car tyre compressor (Osram TYREinflate 450, figure A.3 C) that can be powered from car's 12V cigarette lighter socket, is used, with the purpose of having an auto stop when sufficient pressure is reached. In practice the needed pressure was very low (compressor display showing 0.6 bar) and the automatic stop was quite imprecise - it was best to set it to 0.3 bar and sometimes it overshot to 0.6, if it didn't then starting it for second time raised the pressure enough. Experimenting with higher pressure during the testing led to inner tube glue joint bursting in a place less protected by the textile hat. Figure A.5 shows the hat after repair.

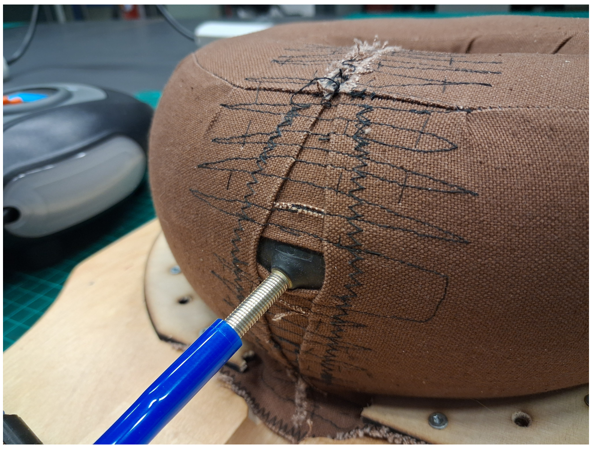

Figure A.5: Wheelbarrow inner tube with a bicycle valve glued on, housed inside a fabric ”hat”/outer shell

The practical height difference achieved with the device when a person weighing about 65 kg was sitting on top was 40-60mm, plus the board thickness, depending on the air pressure and how soft was the chair surface.

Figure A.6: Height of the device in deflated state is approximately 50 mm, in inflated state approximately 100 mm

Appendix 7: Description of prototype "Conveyor"

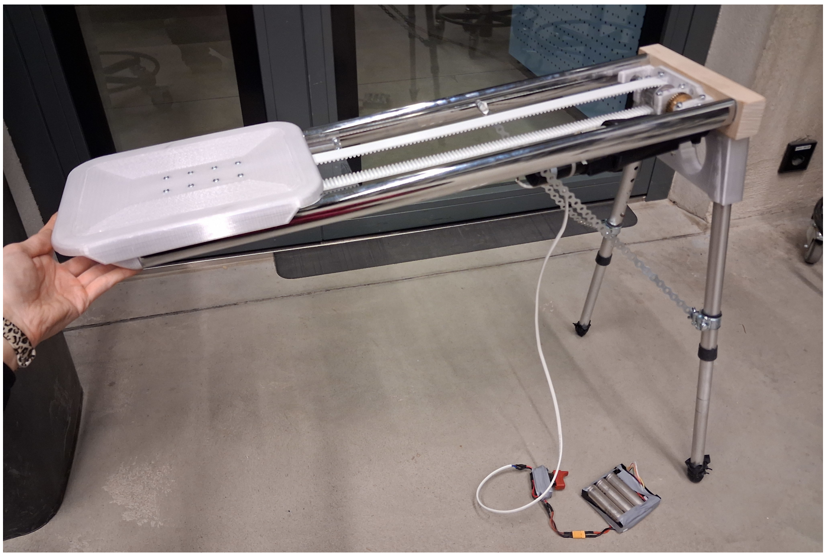

Figure A.7: Prototype *conveyor*

The device consists of metal pipes (for wardrobe, 20 * 35 * 1 mm) as rails on which the seat is sliding. The size of the device frame is 772 x 200 mm and the seat can move 530 mm.

The rails are held together by end pieces. One of the ends has a wedge shape and is meant to be supported on the seat like usual transfer board. The other end can be supported on legs and houses the motor underneath.

The size of the moving seat is 280 * 220 mm and it is made of PETG by FDM printing. Underneath it PTFE strips are attached that facilitate sliding on the pipes (figure A.8). The slots for 2 mm thick and 11 mm wide PTFE strips are made with trapezoidal cross-section and PTFE was carved into similar shape with a carpet knife. The strips slide in from an end and to keep them from sliding out again a bump was created on the PETG seat material using a mixture of cyanoacrylate ("super") glue and baking soda.

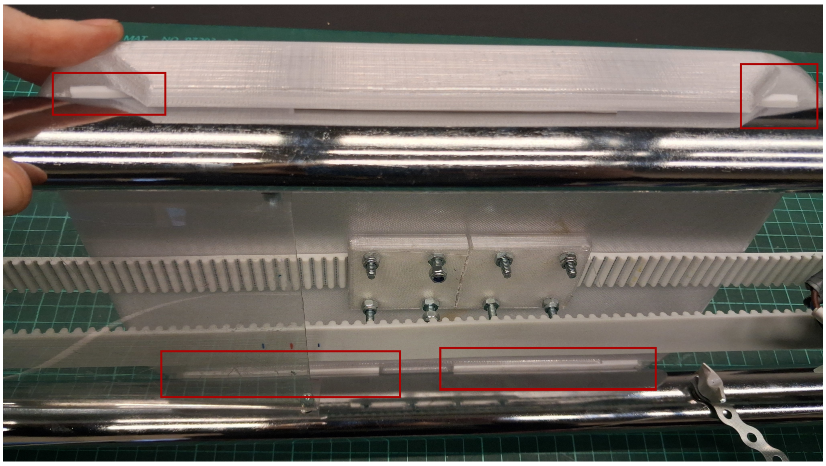

Figure A.8: Underside of the seat. Highlighted in red is placement of PTFE material for sliding on the rails (they are symmetric, one side is only partially visible in the image)

The driving mechanism of the device (figure A.9) is made from 20 mm wide HDT-5M toothed belt, matching 20-tooth belt gear and same size toothed idler in other end, a worm drive (1:36, custom made gear with standard M12x4 trapezoidal screw) and a 12V battery drill motor and chuck. The battery drill's original trigger and direction selector electronics are used. For more portable testing a 3S Li-ion (11.1V nominal) battery set was used.

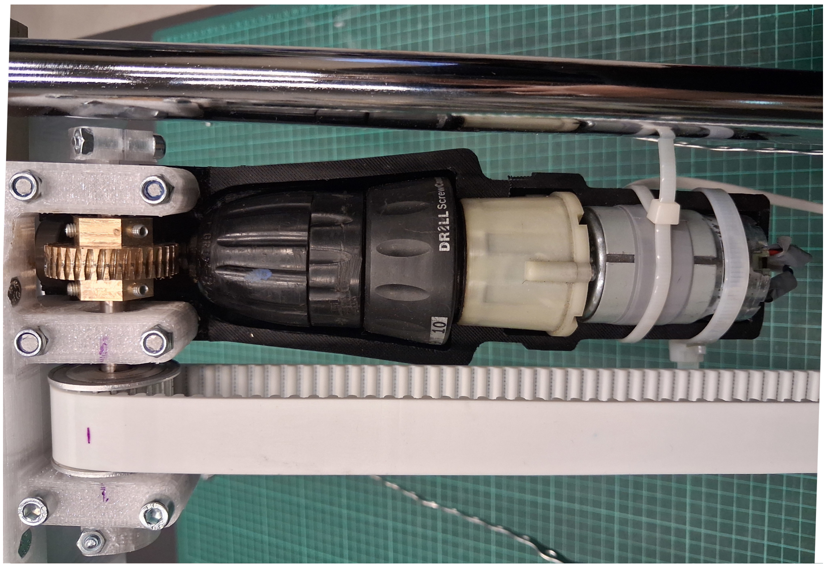

Figure A.9: Battery drill motor with gearbox and chuck, custom made worm drive 1:36, HDT-5M 20 mm belt

This prototype does not have limit switches in the extreme positions. Markings were made on the belt to have visual feedback of the movement limits.

The legs were made of old crutches with adjustable length and a PETG printed part that connects them. The legs are detachable from the rails and main mechanism. Attaching the legs takes aligning them under the end of the frame, then two 8mm steel pins fall into respective holes. Additionally two metal strips have to be attached onto bolts on the inside of the rails, this forms stabilizing triangles where the strips take tension. The strips could be replaced with more flexible cables.

The prototype does not have safety features that a device with such moving parts should have - the area between the rails, except for the belt width, should be covered so that the seat approaching the end parts (that house the belt gear and idler) would not pose a pinch point hazard. Usability questions were not addressed with this prototype and a lot is lacking in that area. For example the attachment of the legs is very inconvenient. Overall the legs attachment is the poorest quality component of the prototype, done with the purpose to only pass a brief testing of the rest of the mechanism. User interface for controlling the motor would be a separate design task for the future if the transport concept would have proved useful.