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Development of requirements for an anthropomorphic shake doll and design of an artificial joint for investigating the infant's body kinematics during shaking.

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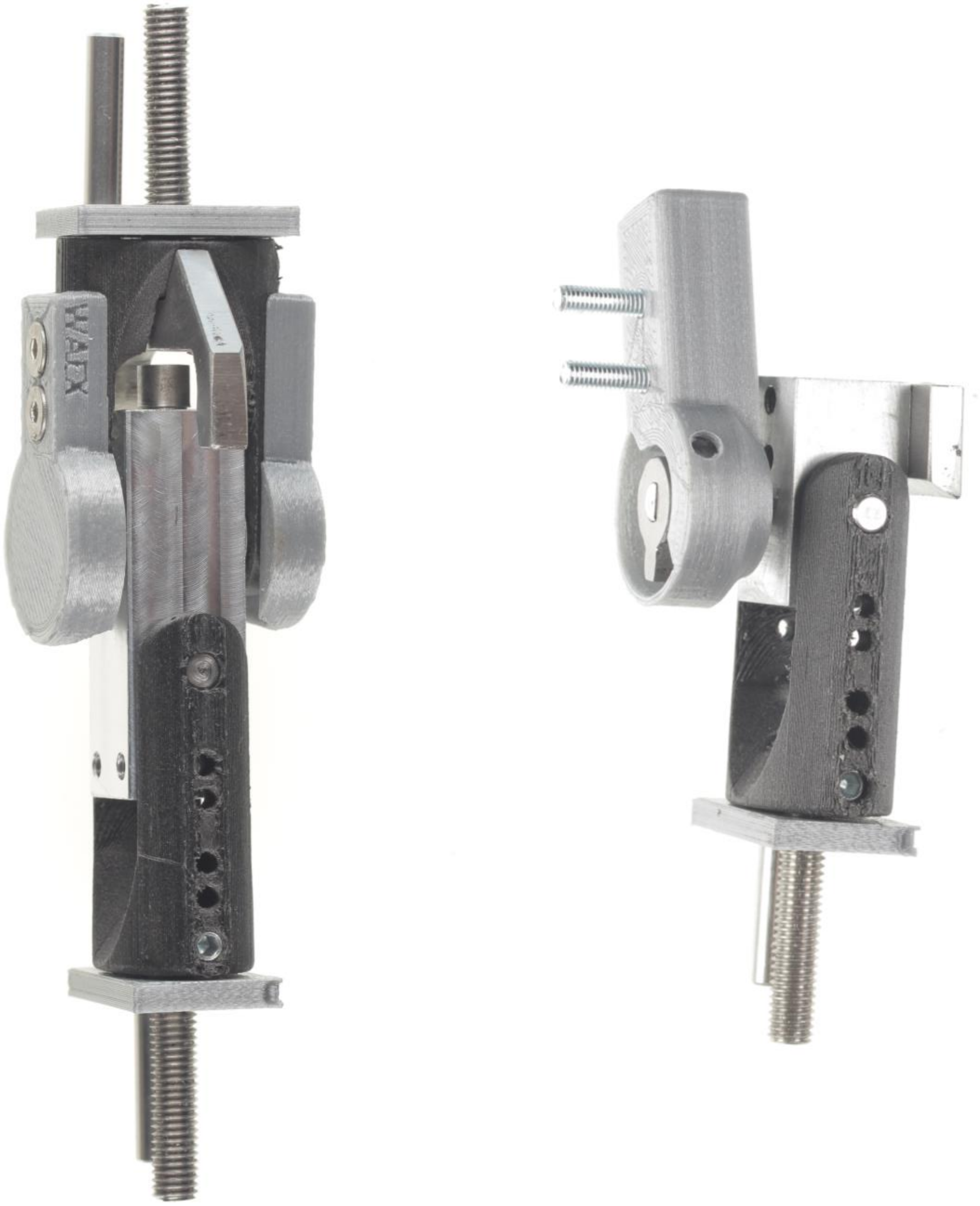

TU Delft

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by

Eva Aranka Blom

to obtain the degree of Master of Science
in Biomedical Engineering at the Delft University of Technology,
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TU Delft

Preface

Helping in the forage transport company of my grandpa and dad, I was directly caught by the huge amount of engineering they used to satisfy their clients as best as possible. Our truck, trailer and crane were all adjusted according to the ideas of my dad, grandpa and craftsmen around them into a well-working combination of techniques and a system which could easily drive through the swampy land and drops straw and hay directly on the most convenient places for the farmers by the use of a crane, roll-in matt or small conveyor belt. This allowed the farmers to easily peddle the straw and hay over the land or stack the bales in a high attic. These options were very advantageous for our customers and a large part of their reason for ordering at our company.

For me, this was a very special, instructive and hard working period in my life, in which my brother and I helped a lot in the company and learned a lot about working together and working for customers. In our company, the communication within our family was very important as well. My mother directly played a key-role in this by building up a safe and cosy home situation in which there was always room for new ideas and enthusiastic plans. She showed us that you should always follow your dreams by for instance following an extra study if you are interested in this. Also at home by my mother's parents, engineering played a major role. My grandpa was a teacher in various technical courses at the technical school, he always challenged me with various math and physics experiments.

After all these influences, it was no surprise that I chose a technical study program during my secondary school. Helped by my teachers of the technical courses, I fulfilled the transition from 3 HAVO to 4 VWO and got my diploma. Afterwards I started with one of the broadest technical studies of the TU Delft, Mechanical Engineering. There, I enjoyed the time during my bachelor with my friends, by doing nice things such as canoeing and wild camping, while also making long days working hard at the TU Delft.

Based on my upcoming interests in designing and building new medical devices, I chose to follow the Master's program Biomedical Engineering with the specialisation 'Medical Instruments and medical Safety'. The obligatory courses of the track 'Biomaterials and Tissue Biomechanics' were also interesting to follow and I really enjoyed the courses. At the same time I decided to start with the Master's program Forensic Science at the UVA, because of my increasing interest in the combinational field between forensics and engineering. From a young age, I was interested in standing up for the interests of people, because everyone deserves a fair trial and all victims deserve good research in which everything is being done to find out the truth. The courses provided by the UVA were very interesting and I enjoyed taking in all the new information, sometimes it was even hard to stop asking questions in lecture.

In line with all these interests I decided to contribute to the research to the kinematical effects on the infant's body during shaking movements, to create more clarity in cases in which it is suspected that head injuries are inflicted by adults while shaking an infant. I found this research to be very interesting, as it allowed me to show and use my research skills and logical thinking to set up a requirements list of an anthropomorphic test doll with which shaking experiments could be performed. This will help us to better understand the effects of such shaking. I was also able to use and develop my designing skills during this project by designing the joints of this model and creating prototypes.

In the future, I hope to soon be able to graduate for my second master Forensic Science at the UVA, finishing my research on the origin of scratch lines in human costal cartilage created by knives during stabbing. Besides this, I hope that after my studies I will be able to work in the forensic technical field. So that I can do interesting case research and be able to contribute to fair trials and research that attempts to uncover the truth.

Eva Aranka Blom
Delft, August 2021

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Abstract

Infant shaking can cause serious damage (inflicted head injury by shaking trauma), it's occurrence indicates the necessity for infant protection. To ensure reliable jurisprudence, it is important to know the exact consequences of shaking on an infant's body. These consequences can be researched by the use of an anthropomorphic shake doll. With this doll, shake experiments can be performed in order to better understand the kinematics of the body and body parts during shaking. This study aims to establish design criteria for this doll as well as designing, producing and testing the joints for this model. A requirement list is presented, as well as a design for a joint that can be used for the limbs of the doll. To ensure structural integrity of this design, a representation of the joint was created and an indicative mechanical shake test was performed. Building further on this real life prototypes have been made.

Keywords

Inflicted head injury, shaking trauma, anthropomorphic test dummy, design requirements, joint design

Introduction

Shaking an infant can be very dangerous [1]. Severe damage to the infant's head and body can occur as a result of these shaking movements, this damage is called inflicted head injury by shaking trauma (IHI-ST). Examples of effects of these injuries are: stagnation of breathing, epileptic attacks, unconsciousness, throwing up, reduced brain activity, bleeding along the brain, bleeding behind the eyes, bleeding along the optic nerve, retinal bleeding, brain tissue decay, micro fractures at the ends of long bones, bruises and rib fractures [2].

Infant shaking, causing these severe symptoms, is still happening nowadays. In the Netherlands Forensic Institute (NFI), around twenty cases in which shaking is suspected, are analysed yearly [2]. Worldwide the incidence of fatal inflicted traumatic brain injury is 17 for each 10.000 infants (0-2 years old) [3]. An often cited reason for infant shaking is the desperation new parents can have, when an infant continuously cries for a long time [2, 4]. When looking at the infants brought in at the NFI, most of the victims are 12 months or younger, although, sometimes infants of 1-3 years old are brought in [2]. These numbers indicate the necessity of infant shaking prevention in order to protect infants and parents. Therefore, it is relevant to know which injuries could be a result of shaking, to ensure reliable jurisprudence. For this, it is necessary to be able to distinguish between various scenarios, such as softly rocking forth- and backward as opposed to actual rough shaking. To distinguish between these scenarios, research to the body's biomechanical response on the inflicted shaking movements needs to be performed. Both the dynamics (the body's reaction to applied external forces) and kinematics (the movements of the body as a result of these forces) are relevant.

This research could be performed by the use of real infants, animals, simulations or anthropomorphic test dolls. The first two options are ethically undesirable. A computer simulation could be possible, but is difficult to validate. That is because of the fact that for this simulation also the shake movements need to be validated, while an anthropomorphic shake doll could be shaken by real persons. This doll can be used to research the dynamics and kinematics of the infant's body as a result of applied shaking movements. The shaking experiments can be used to investigate how people actually shake an infant and what the kinematic response is of the infant's body on these shaking movements. Multiple sensors on the body parts of the doll and inside the head of the doll can be used to measure these movements and responses. Based on these measurements of for instance bridging vein deformations, bridging vein stress and eye pressure, the response of the infant's body on shaking movements can be derived. That information needs to be coupled to situations in which it is known that damage occurred. This coupling gives more information on the actual shaking situation.

The method of using an anthropomorphic shake doll could lead to less uncertainty than witness/ perpetrator statements, which are more subjective interpretations of the actual situation.

A few infant-dummies have already been developed. In the USA, an infant dummy is developed which is used on schools for creating awareness on the damaging effects of shaking. When the doll has been roughly shaken, light signals will appear in the damaging brain areas, no realistic simulating biological materials are involved in this model [5, 6]. Furthermore, dummies of infants are developed for vehicle crash tests by the 'European Enhanced Vehicle-Safety Committee', called the 'P and Q dummies'. These dummies have joints inside the shoulder and hip (1 Degree Of Freedom (DOF)). In these dummies the head is made of a solid material. No internal head structures such as brain and bridging veins are present from which the kinematics could be measured by the use of sensors. Next to that, limbs and head are not interchangeable with other versions, while their mass and dimensions differ significantly over age [7, 8]. The joints and neck are also not interchangeable with other versions, with possibly different stiffness, degrees of freedom (DOF) and ranges of motion (ROM) [9-12]. Adding such modularity would allow for case-specific research. Another dummy of an infant body, developed by Duhaime (1987), has an interchangeable neck. The neck can be represented by a rubber tube with resistance or a hinge without resistance [13, 14]. In this model, the limbs are rigidly connected to the body, which limits the representative value of this dummy for shaking experiments. Because of this rigid connection the influence of the movements of the limbs on the body's movement are not taken into account.

In short, for the design of a realistic anthropomorphic shake doll, the following requirements would represent a great improvement in representing an actual shaking situation and actual response of the body. It should:

- allow for a minimum of two DOF for the joints and adjustability between 0-2 DOFs,
- allow for ROMs which correspond to ROMs of infants,
- allow for interchangeability of head and limbs,
- allow for adaptation of the neck and joint stiffness,
- have internal head structures e.g. brain, bridging veins and eyes.

None of the existing dolls, meets all these requirements. However, they are necessary for researching what actually happens inside and at the outside of the body of an infant while being shaken. The contribution of the limbs needs to be considered, due to their large contribution to the total body weight. This contribution is for males and females of 1 month old and 3 years old respectively approximately: 25% and 33% [15-18]. The large mass contribution shows the influence these limbs have on the body's moment of inertia during shaking. Especially the flexion/extension and abduction/adduction movements of joints are causing displacement of mass. Therefore these DOFs and also their corresponding ROMs need to be considered, to allow for research to the infant's body reaction. For case-research it is desirable to be able to interchange the head and limbs to allow for case-specific research. Also the stiffness of the neck and joints could influence the body's movement and therefore need to be considered. The dynamic behaviour of the inner structure of the head must also be realistic (having tensile, compressive and elasticity parameters similar to real infant's internal structures), to check the influence of the shaking movements on their movements. Another possibility is adding sensors which can measure these parameters.

In this article a start is made with designing and producing an anthropomorphic doll. In the design of the doll, the first focus lays on representing the kinematics, which contains the head's movements as a result of the body's movements due to applied shaking forces. At a later stage the focus can be laid on adding sensors to allow for measuring the kinematics of the body and body parts. Also the dynamics of the internal structures inside the head can be researched at a later stage. For example, on the forces which are applied on the bridging veins and brains during shaking movements as well as when damage exactly occurs.

The goal of this particular research is to set up a requirements list of an anthropomorphic infant model (applicable for case-specific research in the age range of 0-3 years) and set up a list of requirements for it's joints, to be able to design, produce and test joints for that infant model.

Methods

Overall requirements

The situation from shaking movements (input) until the movements of internal structures (output), is summarized in Figure 1. Based on the structure set up in the figure, a list of requirements for the anthropomorphic doll was developed. Steps 6 'Injury thresholds' and 7 'Injury' will not be discussed in this article, because they can only be researched when the test dummy has been build and the actual forces and movements on/of internal structures can be measured in relation to resulting injuries. In addition to this list, a list with general, more overarching requirements that the design must meet is added, called step 'General'. The doll is made for measurements (which are later described) but this study will mainly focus first on the design of the doll, while keeping in mind the necessity of measurement possibilities.

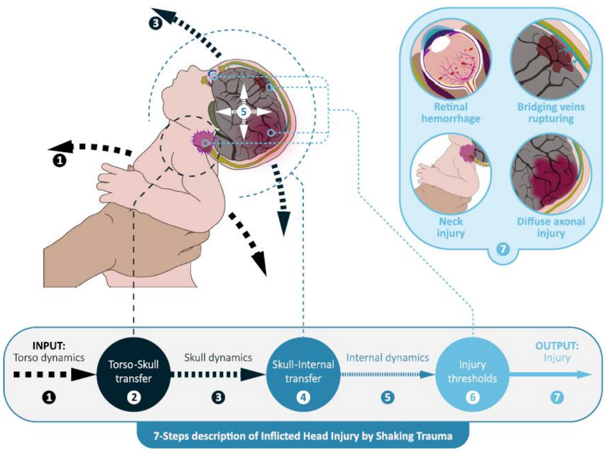


Figure 1. "7-steps description of inflicted head injury by shaking trauma in children" adopted from van Zandwijk et al. (2019) [19].

For steps 1 to 5, the available information concerning these subjects in relation to 0-3 year olds has been searched and presented. Google Scholar, PubMed and Scopus were used for searching this available information on these subjects. Furthermore, based on the advice of various paediatric physiotherapists [20, 21], three books were consulted: 'Thieme Atlas of Anatomy' (Schuenke, M., 2015), 'Joint Range of Motion and Muscle Length Testing' (Reese, N.B. and Bandy, W.D.) and Kinderfysiotherapie' (van Empelen, R., Nijhuis-van der Sanden, R. and Hartman, A.) [22-24]. The information which is yet to be determined concerning the subjects of the steps is described. Next to that, the assumptions which could be made are given. Lastly, the working requirements, which are the practical requirements which will be used to design the doll, were set up for each step. They represent the requirements the doll needs to meet to create a minimum, a desired and an ideal representation of an infant's body:

- Minimum: simulating the body's kinematic reaction to shaking movements in such a way some current dolls allow (e.g. with 0 DOF joints/ stiff joints). A doll which meets these requirements gives a rough indication of the reaction of the infant's body on shaking movements. These results can be used when the desired or ideal requirements cannot be achieved.
- Desired: simulating the body's reaction to shaking movements in a more extended way some current dolls allow (e.g. with 0-1 DOF joints/ stiff joints or without stiffness). With a doll that meets these requirements, experiments can be performed simulating the two most extreme shaking situations. The case-specific shaking situation will then lay in between these extreme situations, therefore a good indication with these desired requirements can be given about the actual shaking situation.
- Ideal: simulating the bodies reaction to shaking movements in the most extended way (e.g. with realistic DOF, ROM and stiffness of joints and realistic internal head structures), taking into account all relevant influences on the reaction of the infant's body. Allowing for realistic shaking experiments. This also allows for performing experiments which can be used to check if more than one DOF is making a difference and if the ROMs also have significant influence.

In Table 1, an overview is given of the earlier mentioned steps. For these steps a subdivision in research fields has been presented from which information has been found in literature.

Based on the findings of the Netherlands Forensic Institute (NFI), the age category on which this research is focused on is 0-3 years. Their findings were that most of the infants which are brought in, and from which is expected that they could have been shaken roughly (around 20 cases each year), are under 12 months, sometimes 1-3 years old and rarely 3 years old and up [2]. During this research, when data of this age category was lacking, the search was extended to data retrieved from youngsters (up to 19 years) (when available) or adults (19 years and up). When data is presented of these other age categories, it is made clear in those specific tables to which age category the data belongs, by the use of various underlining (youngster data and adult data). When data of adults or youngsters is presented, no scaling has been performed to convert adult or youngster data to infant data, the actual data is presented in those cases.

Table 1. For each step a short description is given and the research fields are presented.

Step	Step Name	Description (to ensure the following:)	Research fields (parameters)
General	General requirements	Reliable and safe use.	Modular and adjustable
			Safe and robust
			No limited shelf life
			Easy to handle
			Partly re-useable
			Maintainable and repairable
1	Torso dynamics	Realistic application of shaking movements.	Anthropomorphic dimensions of torso
			DOF of joints
			ROM of joints
			Joint stiffness
			Inertial properties of torso and limbs.
2	Torso-skull transfer	Realistic simulation of the kinematics and dynamics of the neck and transfer between torso and skull.	Anthropomorphic dimensions of neck
			DOF of neck
			ROM of neck
			Neck stiffness
			Collision of torso and skull
3	Skull dynamics	Realistic dynamical movements of the skull.	Anthropomorphic dimensions of skull
			Inertial properties of skull
4	Skull-internal transfer	Realistic transfer of forces and movements from the skull to the brain (via the CSF, bridging veins and eyes).	CSF properties: volume, density, viscosity, pressure
			Bridging veins elongation properties: ultimate tensile stress and strain, stress-strain relation, elastic modulus, relaxation behaviour
			Eye properties: peak tensile stress, peak compressive stress, intraocular pressure, elastic modulus
5	Internal dynamics	Realistic internal dynamics of the brain.	The brain: shear storage, loss and complex moduli, shear stiffness and damping ratio, elasticity score, relaxation behaviour, brain volume

Design requirements for the major joints

Besides the requirements list for the entire doll, also a requirements list focused on the major joints (knee, elbow, ankle, wrist, hip and shoulder) was developed. This list was subdivided in mechanical (concerning DOF and ROM), geometric (concerning connection system and dimensions) and general requirements (the overarching requirements for the entire doll).

The requirements list has been build up from the joint information which was found when setting up the overall requirements list for the entire doll. Also for the joints an overview of the working requirements was set up. This overview presents the requirements the doll needs to meet to create a 'minimum', 'desired' and 'ideal' representation of the infant's joints. These three representations were further explained in the method section of the 'Overall requirements'. During the design, the possibility of adding sensors to the limbs and in the head was kept in mind.

Design

For constructing the most promising design, which meets the requirements the best, a morphologic overview was used to determine which possible combinations of concepts could be used for the design of the joints. The morphologic overview was divided in a DOF and ROM (mechanical requirements) and connection system (geometric requirements) section. Afterwards, the various concepts within these sections were compared by the use of a Harris profile for each separate criterion (mechanical, geometric and general requirements). Based on these comparisons the most suitable design was developed. This design was made in a design program called SolidWorks. To allow for checking if all ROMs are reached and DOFs are possible and able to be locked, a prototype is made. Next to that, to allow for an indicative test on the strength of the model, a representation of the design is made of both aluminium and one of micro carbon fiber filled nylon (ONYX, PA12).

Joint tests

To check whether the design meets the mechanical, geometric and general requirements, various tests have been done with the SolidWorks model, the aluminium and nylon (with carbon fibers) models and the prototype.

Mechanical requirements (DOF and ROM)

The DOFs and its adjustability of DOFs of the design of the knee, elbow, ankle and wrist joint and the design of the hip and shoulder joint were derived from the SolidWorks-model and the prototype. This is done by checking if 0, 1 and 2 DOFs are possible to set, by locking 1 or 2 DOFs. Locking is done by the use of a pin which is inserted through the system. This pin prevents movement in one direction.

The ROMs of the model and their adjustability were derived from both the SolidWorks-model and the prototype. The ROMs of the designs can be adjusted by the use of limiters, which are screwed on the design and which prevent movements larger than the specific ROMs for the researched age range. In SolidWorks the 'evaluate tool' is used to measure movement ranges in the model. This tool was used for the measurements within SolidWorks. A protractor was used to measure the ROMs of the prototype, as shown in Figure 2.

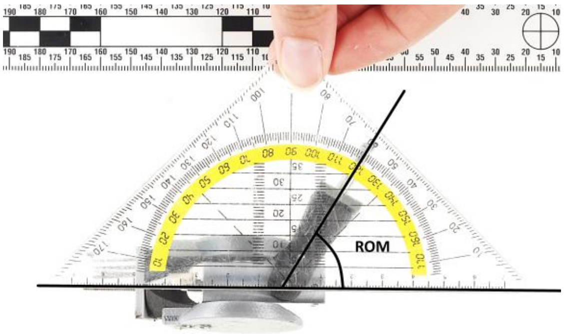


Figure 2. In this figure, the method used for measuring the ROMs of the various joints.

Geometric requirements (connection system and dimensions)

The demount possibility of the connection system is tested by the use of the prototype.

The dimensions of the entire design (including all limiters) were checked in the SolidWorks-model by use of the 'evaluate tool'.

General requirements (overarching requirements)

The safety and robustness were tested with a test setup in which one of the weakest points of the construction is tested in one of the most extreme practical shaking situations. The weakest point was found by checking at which location the largest impact-moment (the moment with the smallest moment-arm) was applied.

One extreme holding situation, concerns the situation in which a 3 year old infant is shaken by holding it at its hand. This is due to the fact that then the largest distance to the centre of mass occurs in collaboration with the heaviest weights, this causes one of the most extreme impact moments of the yoke on the limiters of the system.
In this test, the infant is represented by weights from which the total mass is at least as large as the mean mass of a male infant of 1, 6, 12, 24, 36 months old; 4.3, 7.6, 10.3, 13.0 and 15.3 kg respectively (Appendix A.4., Table 1 [17]). The male infants were chosen, for their larger mass in comparison to female infants. These weights were attached to a bar which is inserted to an aluminium rod. This rod has various holes, from which the distance matches with the distances to centres of mass of infants of the various ages: 28.0, 32.8, 36.7, 48.1, 51.7 cm respectively (for 1, 6, 12, 24 and 36 months old infants), see Figure 3.

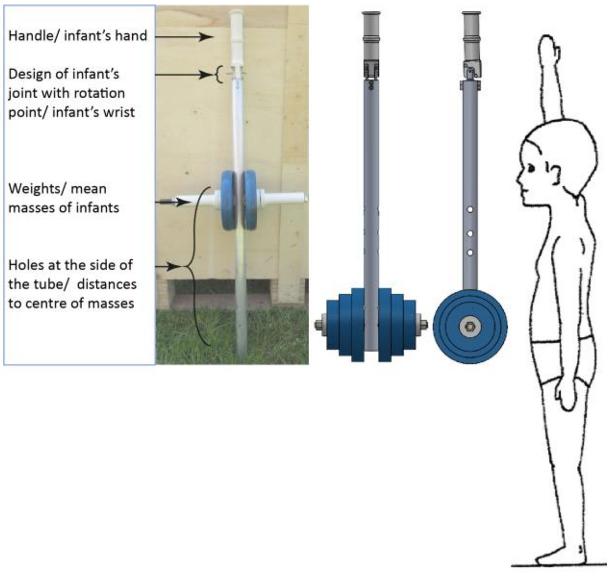


Figure 3. On the left side the used prototype during the indicative shake test is shown, in the middle the SolidWorks drawing of the prototype is visualized and on the right side a drawing of an infant giving an indication of the real life situation is presented.

The distances to the centre of masses are derived from Appendix A.1. Table 1, by calculating the distance of the mass middle point to the wrist. First the crown to the mass middle point was calculated by multiplying 0.424 (mass middle point was 57.6% from total length, measured from the ground [8]) with the stature lengths. Then the head and neck length were subtracted and the underarm and upper arm lengths were added up, while subtracting the hand length (which was in the data combined with the underarm length). The definitions of these terms are shown in Figure 4.

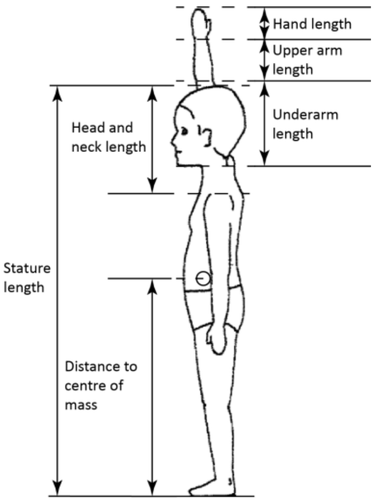


Figure 4. Overview of definitions of terms concerning the lengths of body parts.

A representation of the hand was attached to the design, to allow for a more realistic test, taking into account the limited possibilities of holding the infant by his or her small hand.
An indicative mechanical shake test was conducted, to check if the design would be strong enough to withstand impact forces which occur during shaking. It was chosen to shake as rough as possible aiming for the largest impact of the yoke on the stainless steel pin, which is positioned in the block with the handle, as shown in Figure 5.

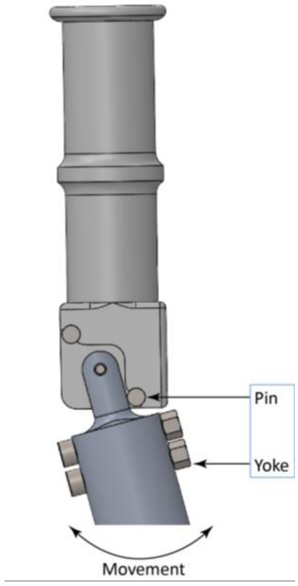


Figure 5. Close-up of impact situation during the indicative mechanical shake test.

Shaken was done as rough as possible, aiming for the largest impact on the design. The amount of shakes which were performed was ten times for each of the five settings, representing the five earlier mentioned ages. One relatively strong person (length: 1.79 cm, mass: 70 kg, BMI: 21.8) was asked to do the shaking test. In this way a rough idea was gained if the design could be strong enough to withstand impact forces which occur during shaking (the form of consent is added in Appendix C).

After each of the five settings, photos were made of the design, focused on the spot at which impact took place, in order to visualize the damage (plastic deformation) which occurred.

The test was repeated for the 3D printed model (Nylon filled with carbon fibers). Similarly photo's has been made at the same way (made at the side of impact).

Results

Overall requirements

The general requirements that the doll needs to meet are:

- the doll should be modular and adjustable in order to:
  - represent children of various builds, within the age range of 0-3 years old, and therefore
    - allow for measuring rigid body movements (for a rigid skull) and for measuring the internal movements of the internal structures: CFS, bridging veins, eyes and brain,
    - allow for replacing or adjusting relevant parts (neck and joints) to vary DOF, ROM and stiffness,

    while minimizing the extent to which measurement electronics have to be replaced, adjusted or recalibrated.
- safe to use and robust, parts do not loosen or break during use,
- no limited shelf life, when stored the doll must remain suitable for experiments for around 10 years,
- easy to handle, it should be clear for future researchers how the doll works and how it needs to be assembled,
- partly re-useable, the basic structure of torso, limbs, skull and neck need to be re-useable while the structures inside the head do not need to be re-useable,
- easy to maintain and repair,
- easy changeable and adjustable to allow for case-specific research, limbs, neck and head are easy to change and the torso's dimensions and mass are easy to adjust,

An overview of the adjustable and interchangeable parts of the doll is given in Figure 6. The overall measurements which need to be able to be performed with the entire doll are also presented in this figure.

Based on the steps 1 to 5 of Figure 1, all research fields of the doll, which influence the body's reaction on shaking movements, and their working requirements are arranged in Table 2. From this table cross references are provided to tables 3-10, which present additional information. A more detailed overview of all available information and working requirements is presented in Appendix A.

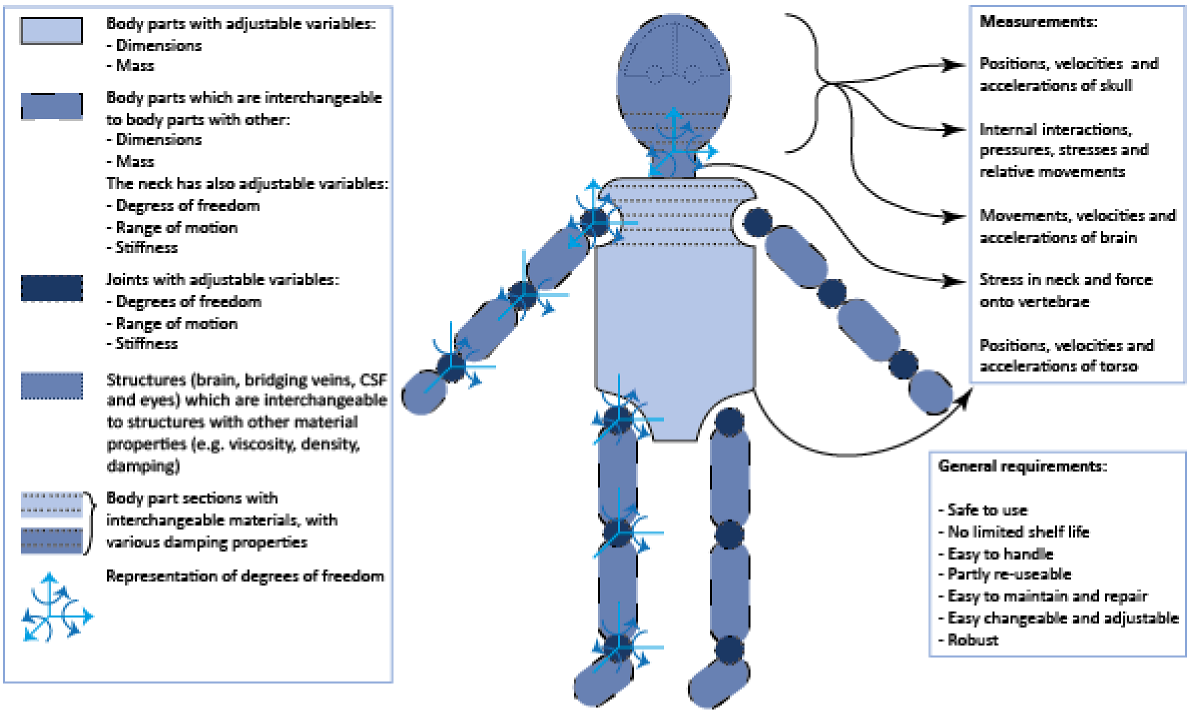


Figure 6. Overview of the requirements for each body part of the anthropomorphic doll, overview of the interchangeable or adjustable body parts, and an overview of the measurements which need to be able to be performed with the doll.

Table 2. Overview of the working requirements of the steps presented in Figure 1. In the table the following abbreviations are used: min.: minimum, max.: maximum, A.: appendix A, T: table, F: figure.

Step Name	Research fields	Working requirements (minimum (m), desired (d) and ideal (i) respectively)	
1. Torso dynamics	Anthropomorphic dimensions of torso	The dimensions of the torso and limbs of the model	m: fall within the min. mean values (youngest infants) and max. mean values (oldest infants) (Table 3)
			d: fall within the min. and max. mean values of the dimensions for each age category (A.1: T1,2).
			i: are adjustable within the range of the min. and max. mean values (Table 3).
	DOF/ ROM/ stiffness of joints	Presented in Table 4 and more extensively in A.2.:T1, A.2.:F1,2, A.3.:T1,2	
	Inertial properties of torso and limbs	The values of the dimensions, segmental mass, radius of gyration, inertia and location of mass centre	m: fall within the min. (youngest infants) and max. mean values (oldest infants) (Table 3, Table 5).
			d: are similar as given for each age category (A.1.: T1,2, A.4.: T1,2, A.5.: T1,2, A.6: T1).
			i: are adjustable within the range of the min. (youngest infants) and max. (oldest infants) mean values (Table 3, Table 5).
2. Torso-skull transfer	Anthropomorphic dimensions of neck	Similar as described in step 1 (first subentry), but focused on the neck instead of the torso and limbs (Table 3 and A.1.: T1,2).	
	DOF/ ROM/ stiffness of neck	DOF, ROM and stiffness data of the neck and their working requirements are presented in Table 4 and more extensively presented in A.2.: T1, A.2.:F1,2, A.3.:T1,2.	
	Collision of torso and skull	Material of chin, left and right side of skull, upper front- and backside of torso (chest) and upper-sides of shoulders is interchangeable:	m: -
			d: and has similar damping properties as human material.
			i: and has similar damping properties as real infant's material.
3. Skull dynamics	Anthropomorphic dimensions of skull	Similar as described in step 1 (first subentry), focused on the skull (Table 3 and A.1.:T1,2).	
	Inertial properties of the skull	Similar as described in step 1 (fifth subentry), focused on the skull (Table 3, Table 5 and A.1.: T1,2, A.4.: T1,2, A.5.: T1,2 and A.6.: T1).	
4. Skull-internal transfer	CSF properties: volume, density, viscosity, pressure	The following properties of CSF are used in the model (respectively: volume, density, viscosity, pressure)	m: 20 ml [25], 1 g/ml for both CSF and brain, 0.6913 mPa*s (water), 3-4 mmHg [25].
			d: all described by 'm' and 1.0431 g/ml for brain [26], 0.7-1 mPa*s [27].
			i: all described by 'd' and adjustable volume within range for neonates (8 ml) and adults (26 ml) [25] and adjustable pressure within 3-4 mmHg [25].
	Bridging veins elongation properties: ultimate tensile stress and strain, stress-strain relation, elastic modulus, relaxation behaviour	m : elongations are represented by marking points on the inside of the skull and outside of the brain (relative movements could be measured).	
		d: bridging veins elongations are represented by a real connection between the skull and brain with similar ultimate stress and strain, yield stress and strain and elastic modulus (Table 6 and A.7.: T1-4).	
		i: all described by 'd' and realistic relaxation properties (Table 6 and A.7.: T1-4, A.7.: F1).	
	Eye properties: peak tensile stress, peak compressive stress, intraocular pressure, elastic modulus	The eye is represented by a material which has	m: intraocular pressure (8.9 mmHg (<1 year), 9.8 mmHg (1 year), 10.4 mmHg (2 years) and 11.5 mmHg (3 years) [28]
			d: all described by 'm' and realistic mechanical and material properties (Table 7), max. peak tensile stress at posterior side of 0.62 kPa [29], max. peak compressive stress at posterior side: around 0.85 kPa [29].
			i: all described by 'd' and adjustable intraocular pressure within 8.9 – 11.5 mmHg [28].
5. Internal dynamics	The brain: shear storage, shear loss and complex moduli, shear stiffness and damping ratio, elasticity score, relaxation behaviour and brain volume	The brain is represented in the model by a material with	m: similar elasticity (elasticity scores (neonates): ventricle 1.0, Subdural space 1.0, Periventricular white matter 4.0, Caudate 4.3, Subcortical white matter 4.0 and cortical grey matter 3.0 [30, 31]). The volume of the total brain falls within the volume values (of the youngest till the oldest infants) of the total brain volume (TBV) (Table 8) (A.8.: T7)
			d: similar mean shear moduli (Table 9), stiffness moduli, damping ratios (Table 10), elasticity scores as described by m and volumes for the various brain regions (Table 8) (A.8.: T1-7)
			i: all described by 'd' and similar relaxation behaviour (decreasing shear modulus by increasing time after application of load [31, 32]) (A.8.: T1-7, A.8.: F1,2).

Table 3. Brief overview of the anthropomorphic data of the torso, limbs, neck, head and combinations of them of infants in the age ranges of 0-2 months and 24-42 months [8].

Body part	Age range (months)	0-2 [8] Mean dimensions (cm)	24-42 [8] Mean dimensions (cm)	Body part	Age range (months)	0-2 [8] Mean dimensions (cm)	24-42 [8] Mean dimensions (cm)
Torso	Shoulder breadth	16.7	24.4	Limbs (2)	Shoulder-elbow length	10.9	18.5
	Biacromial breadth		21.9		Acromion-radiale length		16.7
	Shoulder circumference	45.4*	64.5*		Upper arm circumference	11.8	15.8
	Chest circumference	37.1	50.7		Upper arm depth	5.0	4.7/ 6.6*
	Chest breadth	12.2	16.1		Elbow-hand length	14.9	24.4
	Torso depth	9.5*	12.3*		Radiale-stylion length		13.5
	Natural waist circumference		47.0		Forearm circumference	11.8	15.7
	Waist circumference	34.4	48.1		Forearm breadth		4.7
	Waist breadth	11.6	16.1		Wrist circumference	9.1	11.3
	Hip circumference	36.8	51.7		Wrist breadth		2.9
	Hip breadth	13.2	18.0		Hand length	6.8	10.5
Limbs (1)	Rump-sole length	23.1			Hand Breadth	3.7	5.1
	Pelvis height		51.4	Neck	Neck circumference	21.4*	23.8/ 23.2*
	Hip height at buttocks		40.4		Neck breadth	5.7*	7.1/ 7.4*
	Trochanteric height		42.6		Neck depth	6.1*	6.9*
	Gluteal furrow height		37.5	Head	Head circumference	38.5	49.5
	Rump knee length	13.9			Head breadth	10.4	13.4
	Upper-thigh circumference		29.1		Head length	13.4	17.5
	Upper-thigh depth		8.5		Head height	13.6*	17.3/ 17.9*
	Mid-thigh circumference	16.9			Chin to back circumference	43.3*	55.1*
	Mid-thigh depth	5.2			Chin to back distance	16.1*	20.9*
	Knee-sole length	14.9			Maximum face breadth	8.8*	10.4*
	Tibial height		22.3	Total lengths and combinational lengths	Crown- sole length	56.3	93.4
	Calf circumference	13.7	20.6		Crown-rump length	39.1/ 40.0*	55.1*
	Calf depth		6.2		Suprasternale height		72.4
	Ankle circumference	10.2	14.8		Chest height at axilla		65.2
	Ankle breadth	3.0	4.1		Waist height		49.3
	Foot length	8.2	14.7		Shoulder to head length	14.9*	19.4*
	Foot breadth	3.6	6.1		Shoulder circumference point to head length	17.5*	24.0*

When data was missing in the data of Snyder (1977), which was based on research to 4200 participants and 557 participants of 0-4 years old [8], the parameters were supplemented by data of Schneider (1986), and marked with an asterix (*). The latter data was based on research to 300 participants of 2 weeks to 48 months old [7]. The data of the youngest infants found by Snyder (1977) was for an age range of 0-3 months old, while the oldest data was for infants of 37 to 42 weeks old. When no infant or youngster data was found, the cell was left blank. In appendix A.1. Tables 1 and 2 the ranges of data are given and the age categories are subdivided.

Table 4. Brief overview of the working requirements of the DOF, ROM and passive stiffness (mean values) of human joints. The following abbreviation is used: adj.: adjustable, M: male, F: female.

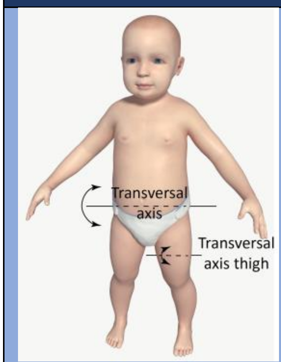
Joint	Movement direction	DOF (-)/ ROM (°)/ stiffness (Nm/ ° and Nm/mm)	*Minimum*	*Desired*	*Ideal*
Shoulder		DOF	0	1	5
	Flexion/ Extension	ROM	-	0°-180°/ 0°-89° (extended arm) 0°-160°/ 0°-50° (abducted arm)	0°-180°/ 0°-89° (extended arm) 0°-160°/ 0°-50° (abducted arm)
		Stiffness	∞	0 or ∞ (adj.)	0, ∞ or 0.007 Nm/° [33]
	Abduction/ Adduction	ROM	-	-	0°-189°/ 0°-40°
		Stiffness	∞	∞	0, ∞ or 0.039 Nm/° [33]
	Internal rotation/ External rotation	ROM	-	-	0°-70°/ 0°-60° (flexed forearm) 0°-90°/ 0°-134° (abducted arm, flexed forearm)
		Stiffness	∞	∞	0, ∞ or 0.024 Nm/° [33]
	Elevation/ Depression	ROM	-	-	0°-40°/ 0°-10°
		Stiffness	∞	∞	0 or ∞
	Protraction/ Retraction	ROM	-	-	0°-30°/ 0°-25°
		Stiffness	∞	∞	0 or ∞

Joint	Movement direction	DOF (-)/ ROM (°)/ stiffness (Nm/ ° and Nm/mm)	*Minimum*	*Desired*	*Ideal*
Hip		DOF	0	1	3
	Flexion/ Extension	ROM	-	0°-143°/ -25°-21°	0°-143°/ -25°-21°
		Stiffness	∞	0 or ∞ (adj.)	0 or ∞
	Abduction/ Adduction	ROM	-	-	0°-63°/ 0°-32° (extended hip) 0°-80°/ 0-20° (flexed hip)
		Stiffness	∞	∞	0 or ∞
	Internal rotation/ External rotation	ROM	-	-	0°-40°/ 0°-50° (flexed hip) 0°-59°/ 0-79°(flexed leg)
		Stiffness	∞	∞	0, ∞ or 0.098 Nm/° [34]
Elbow		DOF	0	1	2
	Flexion/ Extension	ROM	-	0°-158°/ -14°-5°	0°-158°/ -14°-5°
		Stiffness	∞	0 or ∞ (adj.)	0, ∞ or 0.013 Nm/° [35]
	Pronation/ Supination	ROM	-	-	0°-96°/ 0°-93°
		Stiffness	∞	∞	0, ∞, 0.005 Nm/° (M, pronation), 0.002 Nm/° (F, pronation), 0.004 Nm/° (M, supination) or 0.002 Nm/° (F, supination) [36]
Wrist		DOF	0	1	2
	Palmar flexion/ Dorsal extension	ROM	-	0°-96°/ 0°-89°	0°-96°/ 0°-89°
		Stiffness	∞	0 or ∞ (adj.)	0, ∞, 0.011 Nm/° (M, flexion), 0.007 Nm/° (F, flexion), 0.020 Nm/° (M, extension) or 0.013 Nm/° (F, extension) [36]
	Abduction/ Adduction	ROM	-	-	0°-26°/ 0°-41°
		Stiffness	∞	∞	0, ∞, 0.034 Nm/° (M, abduction), 0.021 Nm/° (F, abduction), 0.023 Nm/° (M, adduction) or 0.018 Nm/° (F, adduction) [36]
Knee		DOF	0	1	2
	Flexion/ Extension	ROM	-	0°-159°/ -1°-5°	0°-159°/ -1°-5°
		Stiffness	∞	0 or ∞ (adj.)	0, ∞, 0.501 Nm/° [37]
	Internal rotation/ External rotation	ROM	-	-	0°-10° [22]/ -14°- 4° [38]
		Stiffness	∞	∞	0, ∞, 0.681 Nm/° (M, intern. rot.), 0.663 Nm/° (F, intern. rot.), 0.646 Nm/° (M, ext. rot.) or 0.332 Nm/° (F, ext. rot.) [39]
Ankle		DOF	0	1	3
	Plantar flexion/ Dorsal extension	ROM	-	0°-64°/ 0°-48°	0°-64°/ 0°-48°
		Stiffness	∞	0 or ∞ (adj.)	0, ∞, 0.321 Nm/° (plantar flexion) or 0.526 Nm/° (dorsal extension) [40]
	Pronation/ Supination	ROM	-	-	0°-20°/ 0°-40°
		Stiffness	∞	∞	0 or ∞
	Inversion/ Eversion	ROM	-	-	0°-105° [23, 41]/ 0°-91° [23, 41]
		Stiffness	∞	∞	0, ∞, 0.344 Nm/° (inversion) or 0.492 Nm/° (eversion) [40]
Neck (cervical spine)		DOF	0-1	3	6
	Flexion/ Extension	ROM	0°-65°/ 0°-40°	0°-65°/ 0°-40°	0°-65°/ 0°-40°
		Stiffness	0.14 Nm/° (M) 0.10 Nm/° (F)/ 0.13 Nm/° (M) 0.09 Nm/° (F) [42]	0.14 Nm/° (M) 0.10 Nm/° (F)/ 0.13 Nm/° (M) 0.09 Nm/° (F) [42]	0.14 Nm/° (M) 0.10 Nm/° (F)/ 0.13 Nm/° (M) 0.09 Nm/° (F) [42]
	Lateral flexion	ROM	-	0°-70° [43]	0°-70° [43]
		Stiffness	-	0.15 Nm/° (M, right) 0.09 Nm/° (F, right) 0.16 Nm/° (M, left) 0.10 Nm/° (F, left) [42]	0.15 Nm/° (M, right) 0.09 Nm/° (F, right) 0.16 Nm/° (M, left) 0.10 Nm/° (F, left) [42]
	Axial rotation	ROM	-	0°-112.4° [43]	0°-112.4° [43]
		Stiffness	-	0.089 Nm/° (right)/ 0.084 Nm/° (left) [44]	0.089 Nm/° (right)/ 0.084 Nm/° (left) [44]
	Anterior/ Posterior translation	ROM	-	-	N.A.
		Stiffness	-	-	62 N/mm/ 50 N/mm [45, 46]
	Lateral translation	ROM	-	-	N.A.
		Stiffness	-	-	73 N/mm [45, 46]

Joint	Movement direction	DOF (-)/ ROM (°)/ stiffness (Nm/ ° and Nm/mm)	*Minimum*	*Desired*	*Ideal*
	Vertical tensional/ vertical compressional translation	ROM	-	-	N.A.
		Stiffness	-	-	68 N/mm [45, 47]/ 1876.5 N/mm [45, 48, 49]
Thoracic and Lumbar spine		DOF	0	1	3
	Flexion/ extension	ROM	-	0°-150° / 0°-100°	0°-150° / 0°-100°
		Stiffness		0.70 Nm/° / 0.43 Nm/° (lumbar spine) [50]	0.70 Nm/° / 0.43 Nm/° (lumbar spine) [50]
	Lateral flexion	ROM	-	-	0°-75°
		Stiffness	-	-	1.00 Nm/° (lumbar spine) [50]
	Rotation	ROM	-	-	0°-90°
		Stiffness	-	-	0.33 Nm/° [50]

The data of the ROMs is based on the combination of ROMs of infants in the age range 0 to 2 years old [23, 51]. If no infant data was found, the ROMs of humans in the age range of 18 months to 19 years old are presented, these data are underlined with dots [23, 52]. If no data was available for both infants and youngsters, the data of adults, these data are underlined with a continuous line [22] was used to infer the ROMs. In the table the abbreviations F (females), M (males), intern. (internal), ext. (external) and rot. (rotation) are used.

Table 5. Brief overview of approximations of the mean segmental mass, segmental radius of gyration, segmental inertia (around transversal axis) and location of mass centre (measured from proximal side) of male (M) and female (F) infants [15-18, 53, 54] (N.A.: not available).



	Body part and variable (unit)	Age (months/ years) (Sex F/M)	1/ 0.083 (M)	36/ 3.0 (M)	1/ 0.083 (F)	36/ 3.0 (F)
	Body	Length (cm)	54.7	97.8	54.0	97.0
		Mass (kg)	4.3	15.3	4.1	14.7
	Head and neck	Total segmental mass (kg)	1.2	3.4	1.1	3.2
		Segment radius of gyration (m)	4.4 E-2	6.5 E-2	4.4 E-2	6.5 E-2
		Total segmental inertia (kg*m²)	2.3 E-3	1.4 E-2	2.2 E-3	1.4 E-2
		Location of centre of mass relative to proximal side (%)	N.A.			
	Torso	Total segmental mass (kg)	2.0	6.8	1.9	6.5
		Segment radius of gyration (m)	7.3 E-2	1.1 E-1	7.3 E-2	1.1 E-1
		Total segmental inertia (kg*m²)	1.1 E-2	7.5 E-2	1.0 E-2	7.2 E-2
		Location of centre of mass relative to proximal side (%)	N.A.			
	Upper arm	Total segmental mass (kg)	1.0 E-1	3.9 E-1	9.6 E-2	3.8 E-1
		Segment radius of gyration (m)	3.5 E-2	6.2 E-2	3.5 E-2	5.9 E-2
		Total segmental inertia (kg*m²)	1.2 E-4	1.5 E-3	1.2 E-4	1.3 E-3
		Location of centre of mass relative to proximal side (%)	44.28			
	Forearm	Total segmental mass (kg)	5.8 E-2	2.2 E-1	5.5 E-2	2.1 E-1
		Segment radius of gyration (m)	2.4 E-2	4.1 E-2	2.4 E-2	4.0 E-2
		Total segment inertia (kg*m²)	3.3 E-5	3.7 E-4	3.1 E-5	3.4 E-4
		Location of centre of mass relative to proximal side (%)	45.41			
	Hand	Total segmental mass (kg)	3.8 E-2	1.3 E-1	3.6 E-2	1.3 E-1
		Segment radius of gyration (m)	1.6 E-2	2.6 E-2	1.6 E-2	2.5 E-2
		Total segmental inertia (kg*m²)	1.0 E-5	9.4 E-5	9.5 E-6	8.3 E-5
		Location of centre of mass relative to proximal side (%)	44.95			
	Thigh	Total segmental mass (kg)	1.9 E-1	1.0	1.8 E-1	9.9 E-1
		Segmental radius of gyration (m)	4.0 E-2	NA	4.0 E-2	NA
		Total segmental inertia (kg*m²)	3.1 E-4	NA	2.9 E-4	NA
		Location of centre of mass relative to proximal side (%)	48.59			
	Calf	Total segmental mass (kg)	9.5 E-2	5.3 E-1	9.1 E-2	5.1 E-1
		Segmental radius of gyration (m)	4.4 E-2	6.6 E-2	4.4 E-2	6.9 E-2
		Total segmental inertia (kg*m²)	1.8 E-4	2.3 E-3	1.7 E-4	2.4 E-3
		Location of centre of mass relative to proximal side (%)	43.77			
	Foot	Total segmental mass (kg)	5.9 E-2	2.6 E-1	5.6 E-2	2.5 E-1
		Segmental radius of gyration (m)	2.0 E-2	3.8 E-2	2.0 E-2	3.7 E-2
		Total segmental inertia (kg*m²)	2.3 E-5	3.8 E-4	2.2 E-5	3.4 E-4
		Location of centre of mass relative to proximal side (%)	34.69			

Table 6. Brief overview of the mean strain, stress and elastic modulus of bridging veins [31, 55].

	Yield strain (stretch) (-)	Yield stress (Mpa)	Ultimate strain (stretch) (-)	Ultimate stress (Mpa)	Elastic modulus (MPa)
Low strain rate (1.677 ± 0.242 Hz)	1.240	5.424	1.489	7.204	30.173
High strain rate (15.692 ± 3.446 Hz)	1.256	7.837	1.428	9.885	49.044
Post-cyclic (2.747 ± 0.384 Hz)	1.296	5.758	1.427	7.645	48.106

Table 7. Brief overview of the mean mechanical and material properties of the human eye: elastic modulus, Poisson's ratio and density [56].

Eye part	Elastic modulus (MPa)	Poisson's ratio (-)	Density (kg/m^3)
Cornea	6.1	0.494	1400
Aqueous humor	0.037	0.49	999
Iris	0.5	0.49	1100
Ciliary body	11	0.4	1600
Lens	1.5	0.49	315
Vitreous humor	0.042	0.49	999
Choroid	0.03	0.49	999
Sclera	48	0.454	1400

Table 8. Overview of the mean volumes (mm^3) of various brain regions of various ages [57].

Region	Neonate	1 year old	2 years old
TBV	425.387	855.540	983.866
Cerebral hemispheres	370.685	699.378	804.501
Cerebellum	26.985	91.962	105,154
Subcortical + brainstem	27.679	64.214	73.227
Hemispheric grey	206.480	514.048	588.441
Hemispheric white	164.433	183.280	217.883
Lateral ventricles	2109	8069	7406
Right caudate	NA	3221	3778
Left caudate	NA	3012	3607
Right hippocampus	NA	2113	2377
Left hippocampus	NA	2075	2367

Table 9. Mean shear storage (Pa), shear loss (Pa) and complex moduli (Pa) for brain tissue [31, 58, 59].

	Source	Test	Material	Frequencies (Hz)		
				0.1	1	10
Shear storage moduli (Pa)	Chatelin et al., 2012	Dynamic oscillatory shear experiments (2 and 5 months old human infants)	Brain stem	1100	1480	1700
			Grey matter	400	550	700
			White matter	340	410	700
Shear loss moduli (Pa)	Chatelin et al., 2012	Dynamic oscillatory shear experiments (2 and 5 months old human infants)	Brain stem	260	290	500
			Grey matter	105	115	250
			White matter	80	91	200
	Source	Test	Material	Frequencies (Hz)		
				30	40	60
Complex moduli (Pa)	Yeung et al., 2019	Magnetic resonance elastography (children 7-12 years)	White matter	1110	1470	2150
			Grey matter	1080	1470	2150

Table 10. Mean shear stiffness and damping ratio of various brain regions in adolescents (12-14 years old) [31, 60].

Region	Adolescent		Region	Adolescent	
	Shear stiffness (kPa)	Damping ratio (-)		Shear stiffness (kPa)	Damping ratio (-)
Cerebrum	3.13	0.225	Amygdala	3.49	0.228
Cerebellum	2.48	0.286	Hippocampus	3.25	0.188
Frontal Lobe	2.97	0.216	Caudate	4.11	0.205
Occipital Lobe	2.80	0.269	Putamen	4.00	0.209
Parietal Lobe	2.84	0.247	Pallidum	3.96	0.199
Temporal Lobe	3.01	0.237	Thalamus	4.02	0.192
Deep GM/WM	3.49	0.218			

Design requirements of the major joints

The requirements for both designs of the knee, elbow, ankle and wrist and hip and shoulder are subdivided into mechanical, geometric and general requirements.

Mechanical requirements

The mechanical requirements describe the movements which need to be possible with the joint. The minimum, desired and ideal situation for ROMs and DOFs are defined as the following:

- *Minimum:* no moving of joints is allowed, considered stiff in all directions.
- *Desired:* joint movement of flexion/extension and adduction/abduction is allowed with ROMs of infants of 0-3 years old, these are important DOFs due to their influence on mass displacement. For further research switching between 0-2 DOFs is taken into account, to be able to research the influence of these movement directions on the shaking movements and on the body's response.
- *Ideal*: the joint's DOFs and ROMs of the movements considering internal/external rotations and other possibly additional movements are also taken into account in this *ideal* situation. These DOFs are added, because these ones could lead to mass displacement in the situation in which an infant braces him or herself e.g when bended elbows internal or external rotate. Switching between 0-3 DOFs (flexion/extension, adduction/abduction and internal/external rotations) is taken into account to be able to research the influence of these movement directions on the applied shaking movements and on the body's response to these shaking movements.

The working requirements for DOF and ROM are presented In Table 4. In this table, the infinity and zero signs show which DOF needs to be blocked and which one does not.

Geometric requirements

- Fixation of translations and rotations along longitudinal axis.
- Allow for demounting, so the torso can be adjusted and the limbs can be adjusted or replaced by other ones.
- The diameter of the joint must be smaller than 2.6 cm (smallest mean ankle breadth and smallest mean ankle and wrist breadth (taking into account 1 SD (mean-1SD)) [8]).

General requirements

The general requirements are similar as the ones set up for the entire doll, presented in the 'Overall requirements' section.

Design

The morphologic overview is added in Appendix B. The three main categories of concepts are compared in a Harris profile, shown in Table 11. In Appendix B, Tables 2-5, Harris profiles are presented for the requirements researched in the morphologic overview: 0-2 DOFs, adjustability of DOF and stiffness, adjustability of ROM, demountable connection system.

When comparing the three main concepts as defined in the first row of Table 11, the hinge concept fulfils the criteria the best in comparison to the compliant hinge concept and ball joint concept. This is due to its good adjustability possibilities of the ROM. The compliant hinge concept, has more difficulties with limiting the ROMs, due to its fewer possibilities for adding constant limiters. Besides this, the specified ball joint concept, is not able to reach both the extreme ROMs of infants of 0-3 years old and at the same time having enough socket to still stabilize the ball in it for keeping the system robust and safe. Therefore, the specified hinge concept was chosen to elaborate on further.

Three hinge concepts were compared by the use of the Harris Profile in Appendix B, Table 2. Concluded was that the universal joint concept is the most suitable system to simulate 0-2 DOF movements with extreme ROMs. This concept hasn't got the problem of misalignment of limbs after performing a combinational movement of flexion/extension and abduction/adduction, as the fork joint (incl bearing on shaft) has. For this combinational movement, full rotation along the main (longitudinal) axis is necessary to allow them. The disadvantage of this freedom is the misalignment it causes to the fork joint concept.
An extra bearing along the longitudinal axis of the universal joint concept, which allows an extra DOF (internal/external rotation) can be added to future versions of the model, to give the system an extra DOF. For now this extra DOF is not taken into account, because chosen was to first focus on modelling the flexion/extension and abduction/adduction movements, which cause most mass-displacements during shaking movements. These DOFs have the largest influence on the inertial properties of the infant's body and therefore on the movements of the internal head structures. This follows the same reasoning as the developers of the crash-test dummies in cars, they do not take internal and external rotations of limbs into account either [9-11]. Moreover, they predict that an infant does not brace itself before a car crash impact occurs. Then the mass-displacement as a result of a rotating bended elbow or knee, no longer applies [9-11]. In that case, the model will suffice with 2 DOF: flexion/extension and adduction/abduction.

For the adjustability of DOF, a pin used to limit the DOF (or in other words, add infinite stiffness), was considered to be the most robust and easy-to-handle solution (Appendix B, Table 3). This can be done, by inserting the pin through the system and thus blocking the movements in one direction. In the later presented design, this pin is shown in Figure 7 (Pin 8) and has partly screw thread to be able to fixate one DOF and at the same time it is possible to fixate it in the system.

For the criteria adjustability of ROMs, add-ons and a rod with a pin are the two concepts which were most promising, scoring high on adjustability possibilities and robustness (Appendix B, Table 4). In the later presented design, the add-ons are called flat and normal limiters (Figure 7: parts B and C and Figure 8: parts A and C) and the rod with a pin is designed as a disk with stop pin (Figure 8, part B), having a socket set screw (part 3) which clamps it to the flattened axis (part 2)

For the criteria demountable system, the flattened axis with socket set screw and screw thread and nuts are the two most promising demountable systems. They are modular, adjustable, easy to handle and robust. In the final design a combination of these two concepts is used: the flattened axis with socket set screw is combined with a nut along the screw thread (Appendix B, Table 5). In the later presented design, the socket set screw, flattened axis and nut are shown in Figure 7: parts 4, 2 and 3 and Figure 8: parts 5, 8 and 9 respectively.

All considerations, shown in the Harris profiles, led to the design presented in Figure 7. This design can be adjusted (0-2 DOF and max-min ROM) for the knee, elbow, ankle and wrist. A stand-alone version of the design has been developed for the shoulder and hip, which is presented in Figure 8. This separation into two designs was necessary due to the incompatibility of the combinations of ROM's between these two groups of joints. The shoulder and hip needed extreme ROMs while the other joints didn't need such extreme ROMs and needed specific limiters. Because of this, the limitation of the ROMs of the last group were not able to be limited in the combined design. Therefore two separate designs have been developed, one with enough ROMs for the knee, elbow, ankle and wrist but also possibilities to limit them, and one with more extreme ROMs for the hip and shoulder joints, having the possibility to limit the ROMs for this joint group, these are presented in Figure 7 and Figure 8. In Table 12, the situations with the smallest and largest ROMs are presented for each joint separately.

Table 11. Harris profile set up for the three main categories compared on the mechanical, geometric and general performance.

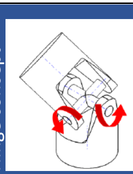
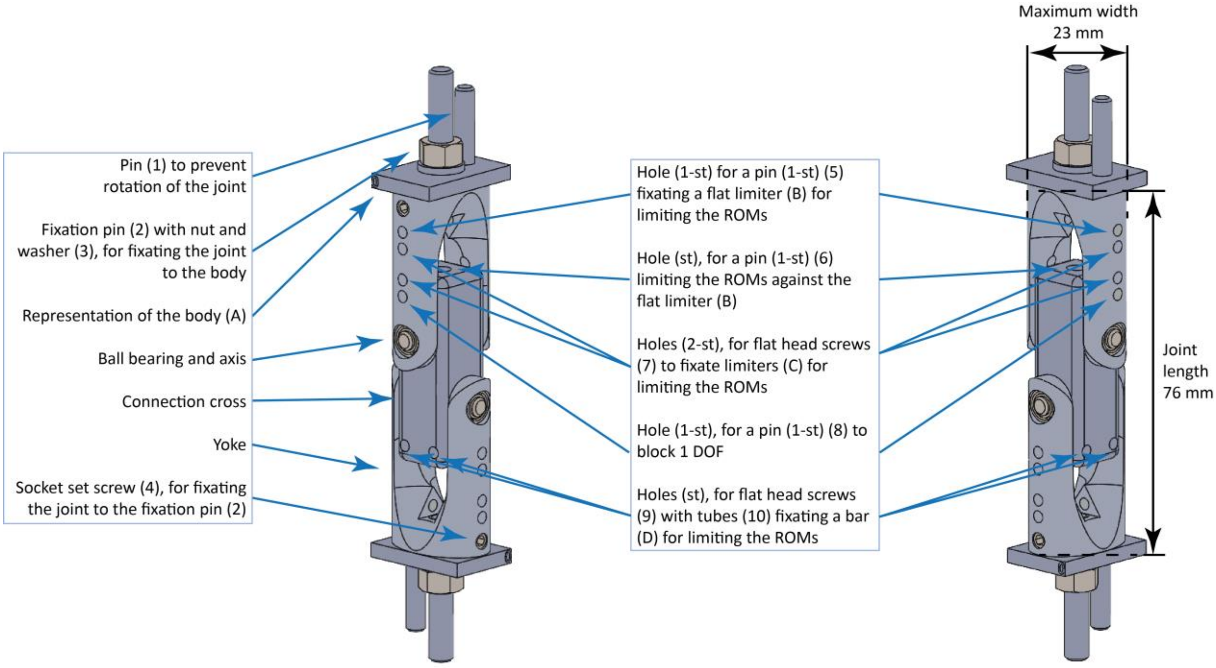
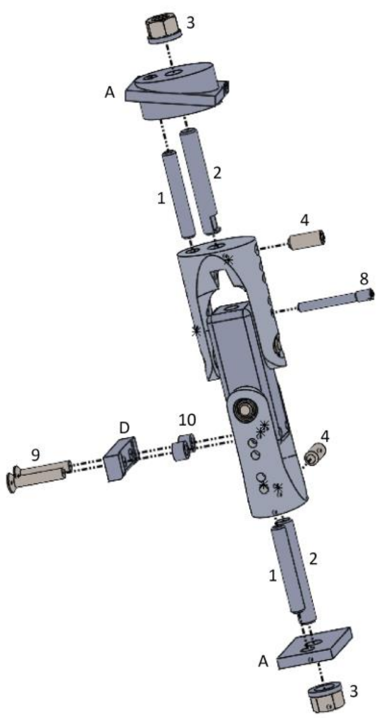
		Compliant hinge concept  [61]	Hinge concept  [62]	Ball joint concept  [63]	Explanation
Mechanical performance	Allows 0-2 DOF movements	++	++	++	
	Adjustability of DOF	++	++	++	
	Adjustability of ROM	+	++	++	For the compliant hinge it is harder to limit the ROM, due to the fewer possibilities to add constant limiters because of the phenomenon that the material is flexible.
Geometric performance	Fixation of translations and rotations	NA	NA	NA	
	Allow for demounting	++	++	++	
	Diameter ≤2.6 cm	++	++	++	
General performance	Modular and adjustable to ROMs of 0-3 year old infants	+	++	++	The compliant hinge concept is not particularly modular and adjustable considering it's ROMs. It is possible to replace the compliant hinge with another one with other properties. The ball joint and hinge concepts, as defined in the upper row, are more modular and adjustable, this is applicable if the socket of the ball joint could be interchanged.
	Safe and robust	++	++	--	The compliant hinge and the hinge concepts, as defined in the upper row, are both safe concepts, no parts can easily loosen during shaking. The ball joint, as defined in the upper row, is not safe due to the limited socket dimensions as a result of the extreme ROMs of infants. Due to these limited dimensions, the ball could easily loosen from the socket
	No limited shelf life	+	+	+	
	Easy to handle	++	++	++	
	Partly re-useable	++	++	++	
	Maintainable and repairable	++	++	++	The hinge and ball-joint, when the socket of the ball-joint is modular, are most easy to maintain and repair due to their modularity. A compliant hinge needs to be replaced when the system is broken or suffers from fatigue.

Figure 7. Final design of the knee, elbow, ankle wrist joint. On the upper side of the figure the basis of the model is explained together with rough dimensions and on the lower part of the figure two exploded views of the elbow (max ROMs) and wrist (max ROMs) joint are shown.





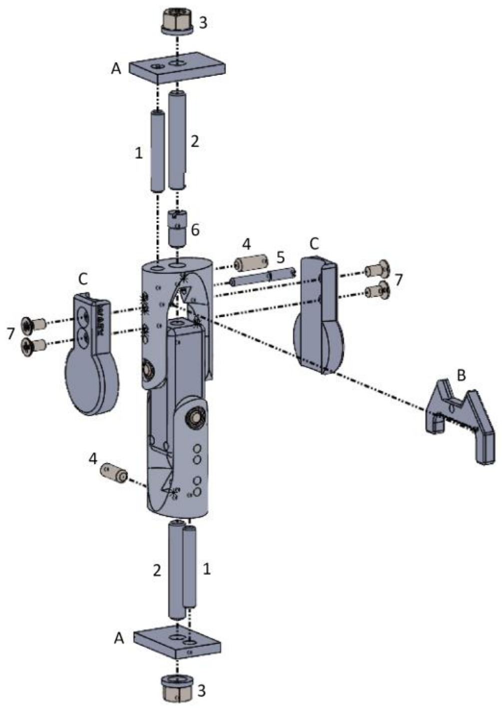


Figure 8. Final design of the hip and shoulder joint. On the upper side of the figure the basis of the model is explained together with the rough dimensions and on the lower part of the figure an exploded view of the hip (max ROMs) is shown.

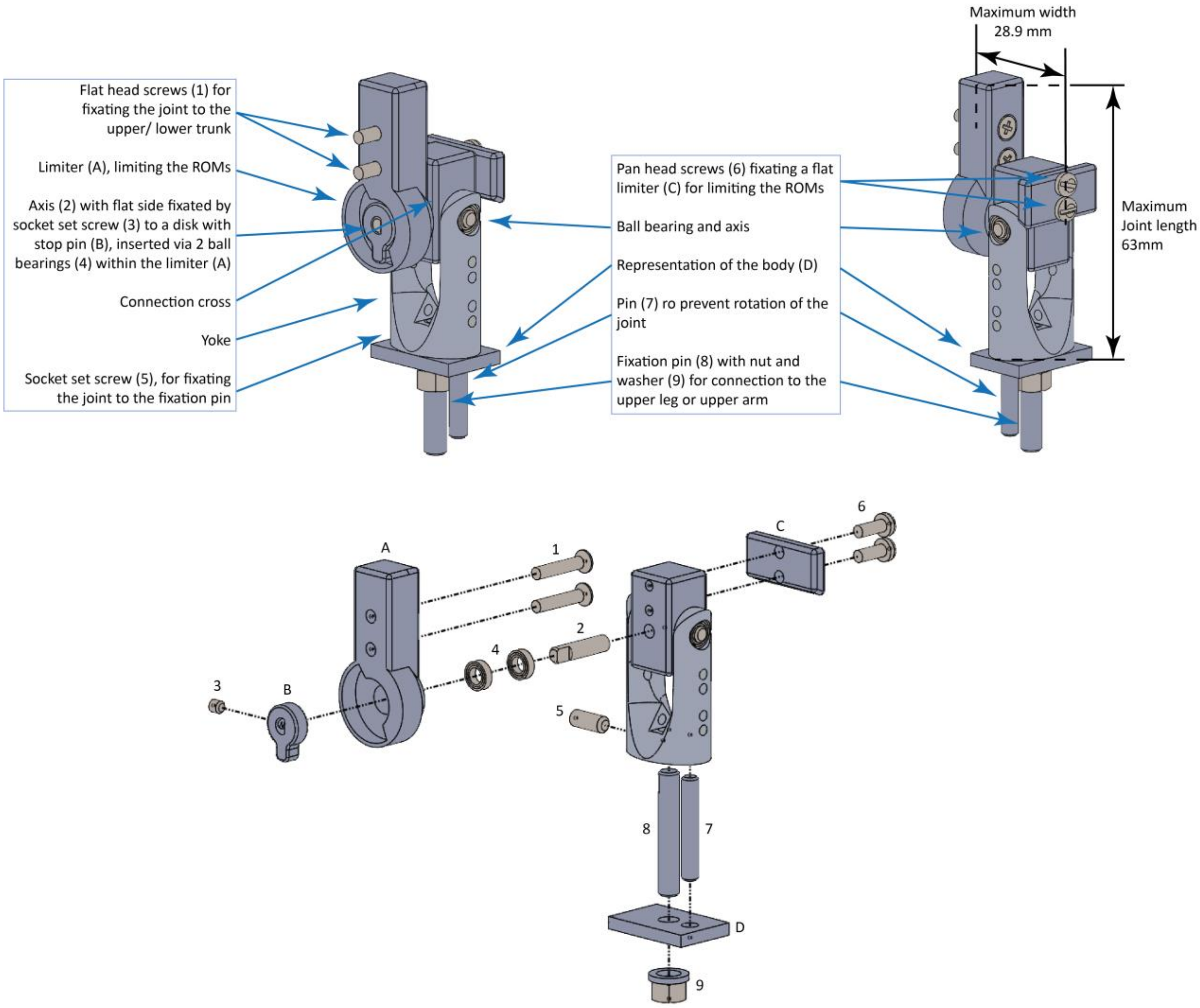
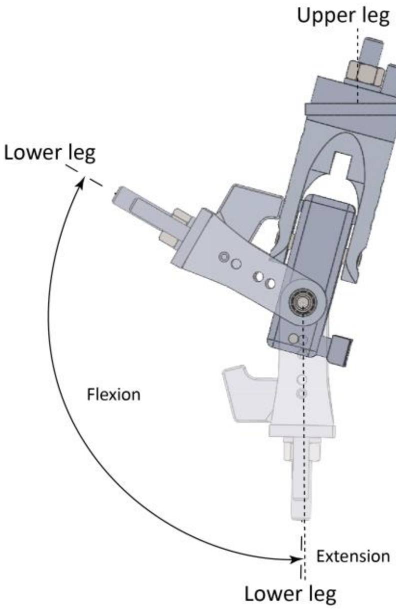
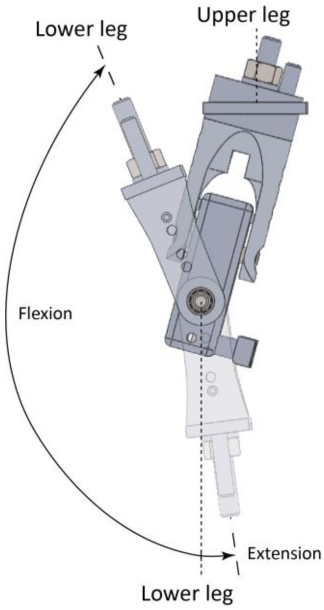
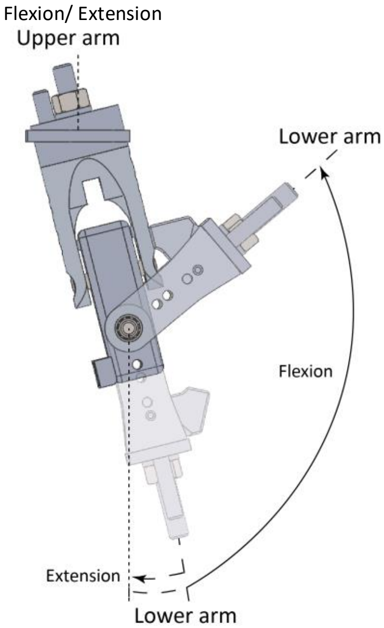
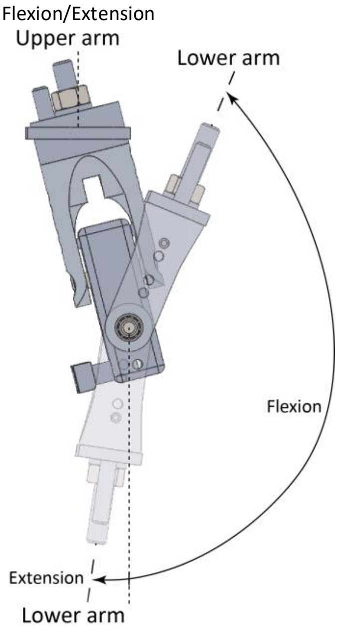


Table 12. Design of knee, elbow, ankle, wrist, hip and shoulder (the selected area and viewpoint is shown in the left column [54])

	Minimum ROM	Maximum ROM
Knee 	Flexion/ Extension 	Flexion/ Extension 
Elbow 	Flexion/ Extension 	Flexion/Extension 

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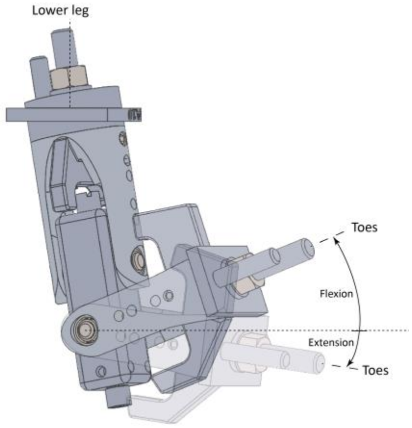
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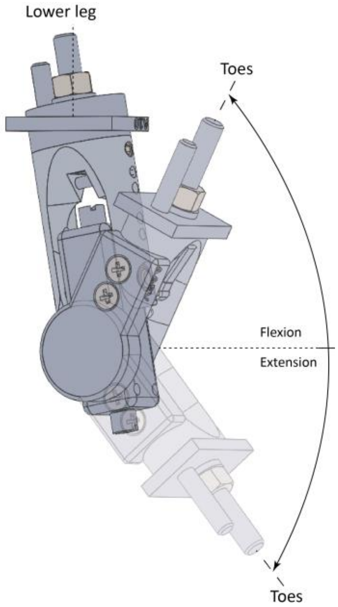
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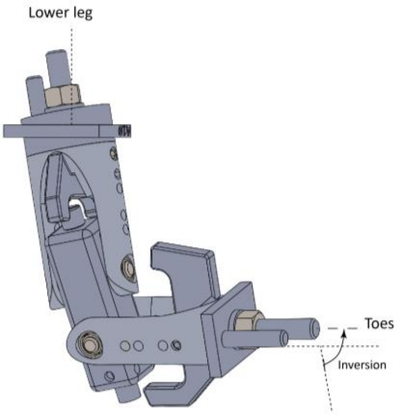
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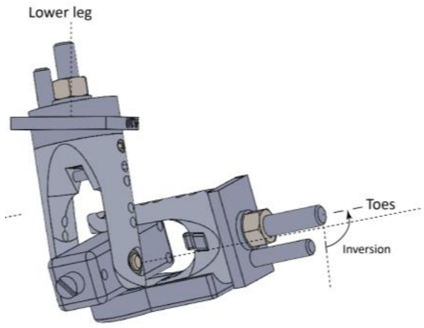
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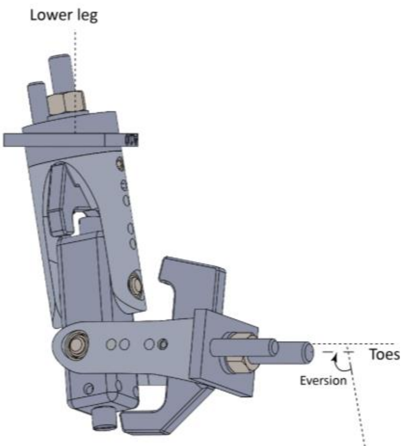
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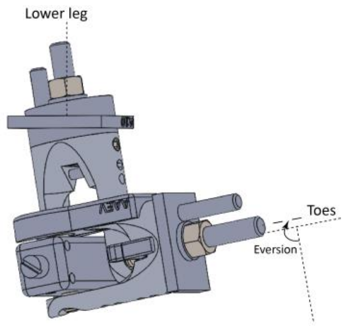
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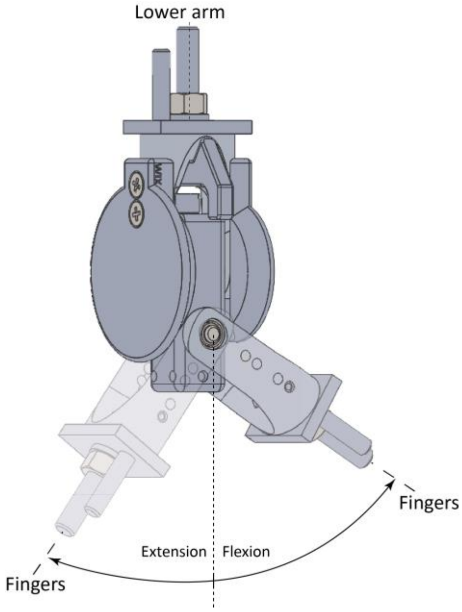
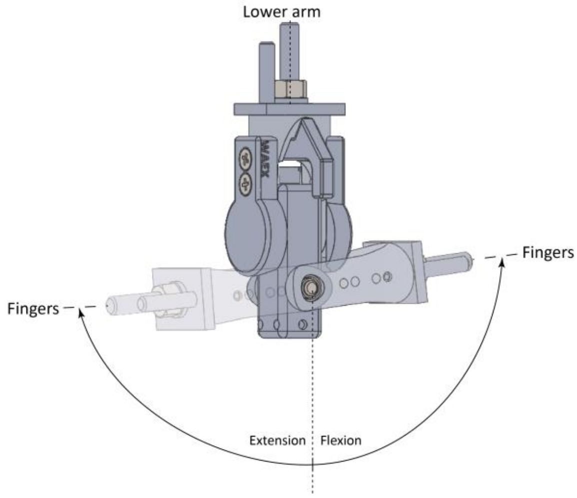
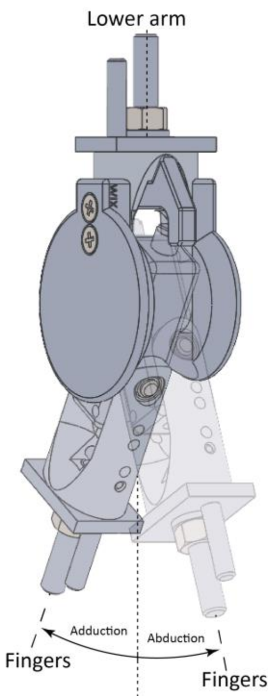
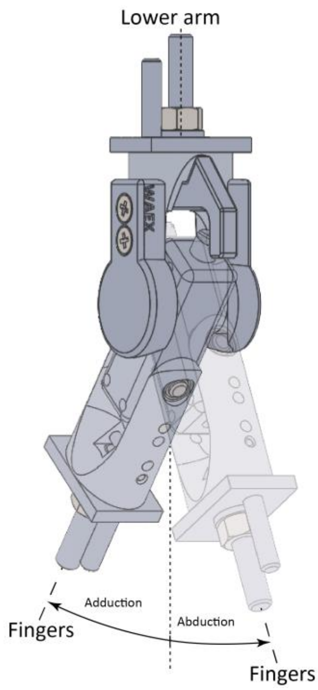
Wrist	Flexion/ Extension	Flexion/ Extension
		
	Adduction/ Abduction 	Adduction/ Abduction 

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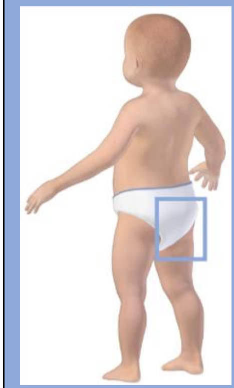</td>
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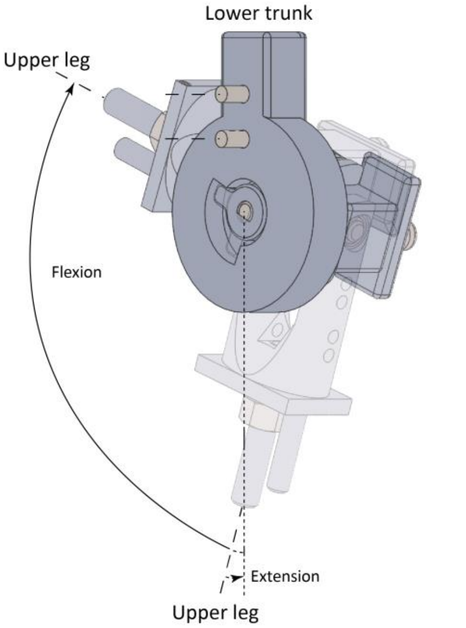</td>
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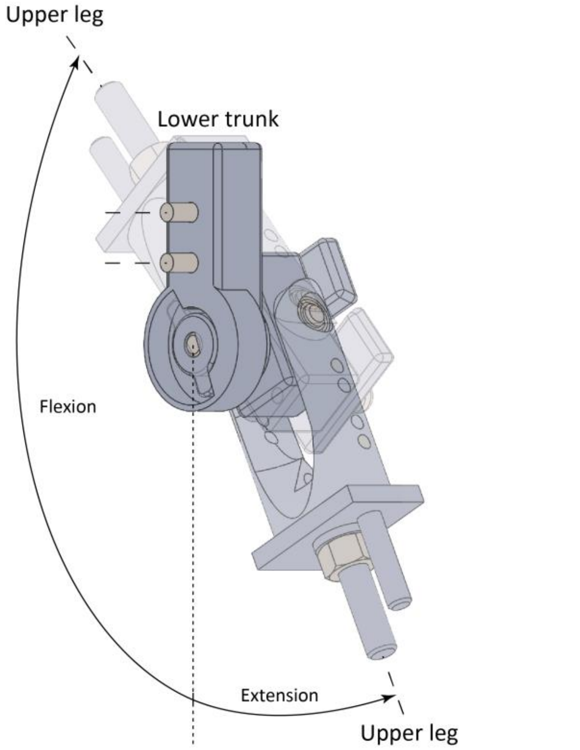</td>
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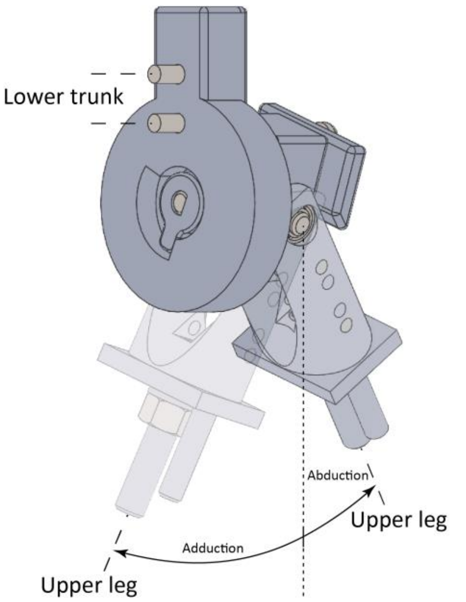</td>
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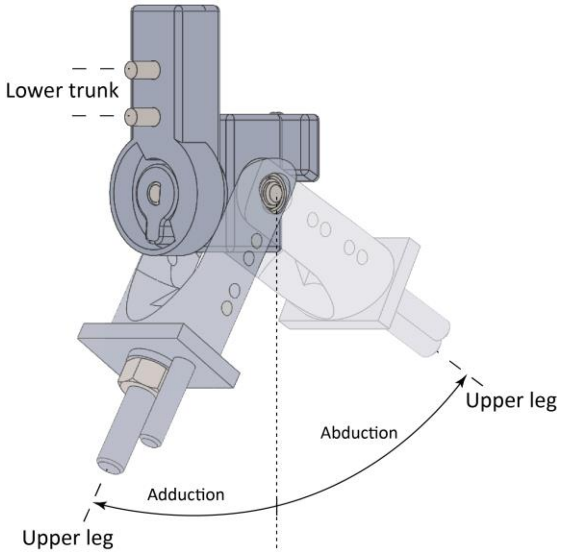</td>
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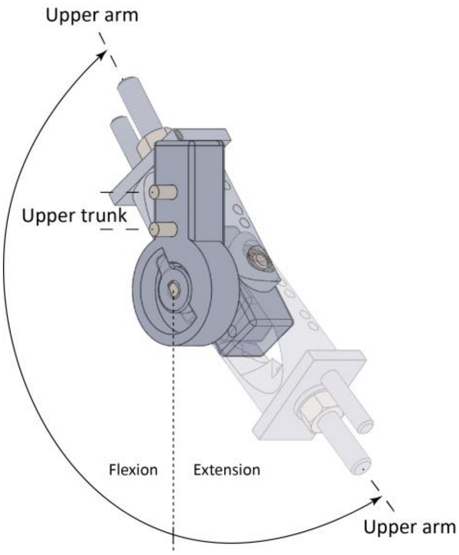
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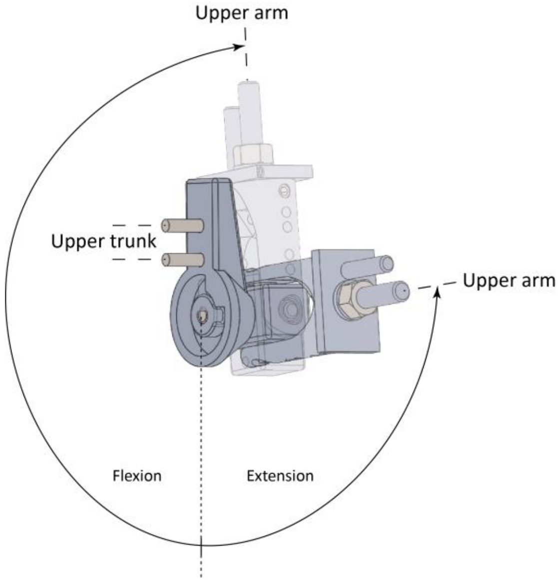
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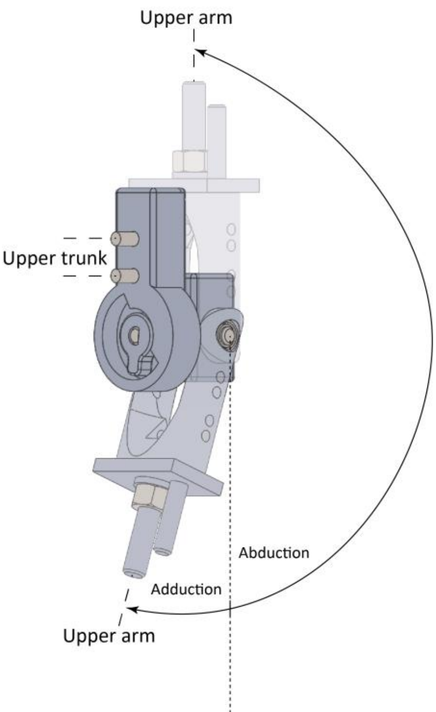
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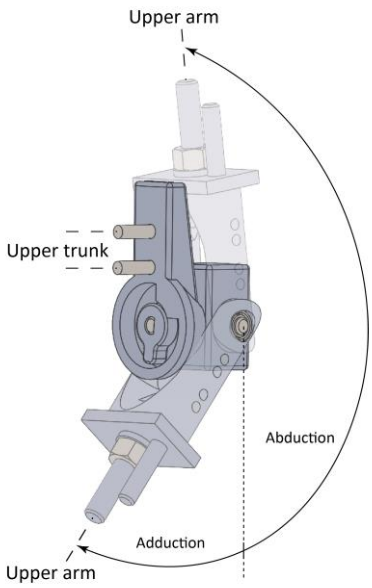
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Design choices

Two yokes were made for the indicative mechanical shake test. Also a full prototype was made of a combination of carbon fibre filled nylon, PLA, aluminium and stainless steel. In a future study, this prototype should be tested if it can handle all forces which are applied on it during shaking movements. If this prototype fails, the yoke and limiters could be made out of aluminium, to increase the strength.

In the prototype the yokes are made out of carbon fibre filled nylon. This material and 3D print technique was chosen due to its strength caused by internal fibres. The limiters are made of PLA, in which they can be accurately printed in the right shape. Both printing techniques give a large design freedom and the easiness of producing more limiters, with other angles, is a large advantage.

The connection crosses are made out of aluminium (AL7075), due to its smaller mass in comparison to stainless steel, relatively high strength and easy manufacturability (CNC milling).

The axis and pins are made out of stainless steel, because they are small while the shear forces on the pins are large. The flat limiters are also made out of stainless steel (laser cutting), which due to the hardness this material offers, edges are prevented to break off. Stainless steel instead of normal steel was chosen to prevent rust.

The post-processing, after 3D printing the yoke and limiters and laser cutting the flat limiters, was done by hand (tailoring the holes accurately and sanding the right angles).

If the 3D printed yoke fails and an aluminium yoke needs to be made, bearings could be used. The bearings which were chosen for the aluminium design are ball bearings. During shaking, movements are chaotic, therefore the turning direction changes frequently. For each reversal, the stick-slip of sliding bearings must be reached before the design actually moves. Therefore ball bearings were chosen, in these bearings this phenomenon is minimal. Next to that, ball bearings can handle impacts much better. In this system there are a lot of impacts against the limiters of the system, which indirectly also cause impacts on the bearings. Therefore their effect need to be taken into account. A disadvantage of the ball bearings is the extra space it takes in the design.

In the joint made of carbon fibre filled nylon (for the prototype) no ball bearings were used. This was due to the sliding possibilities the nylon material has and the limited availability of space.

The drawings of all parts and a list of parts which need to be bought, are presented in appendix E.

Joint tests

In SolidWorks an indicative simulation was conducted for checking the ROMs and DOFs in the 3D models. The models of the various joints all achieve the pre-defined ROMs and DOFs. In some cases the design needs an extension piece which angels the joint to be able to fully reach its ROMs. The prototype is used to check if in the real system also the ROMs were achieved and the DOFs could be blocked. The result was that the DOFs could indeed be blocked. The ROMS were all achieved, only the flexion and extension of the hip and shoulder joint were 2 degrees larger than designed. This was due to the fact that the limiter was a bit damaged by the laser cutter and polisher, therefore their ROMS were a bit larger. Fixation of translation and rotation around and along the longitudinal axis is also possible with the design. Besides, the system is also demountable. Some specific dimensions exceed the max diameter of 2.6 cm, which causes the joint to stick out a bit.
All the results are presented in Table 13. All photo's of the prototype in the various extreme movement configurations are shown in Table 14, Table 15 and Table 16 and the corresponding viewpoints are shown in Figure 12.

A pilot indicative shaking test was conducted with the aluminium and carbon fibre representations of the yoke. In Figure 9 the testing situation is showed and in Figure 10, a close-up of the situation is shown.

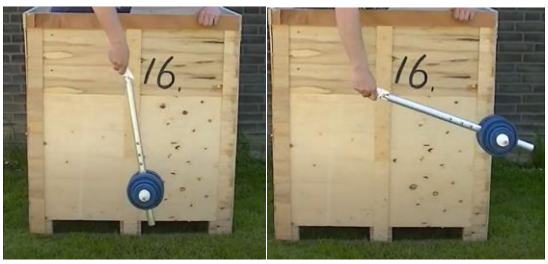


Figure 9. Test situations during shaking, on the left during the shake and on the right side during impact of the yoke on the pins in the block.

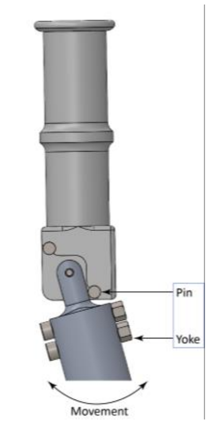


Figure 10. Close up of testing situation.

The aluminium yoke was still intact after the five shaking tests, consisting out of 50 (5 times 10) shakes (with the settings of the five different ages). Only a very small indentation was visible on the model, shown in Figure 11. The carbon fibre 3D printed yoke was tested as well, with a plastic block, without stainless steel pins. This yoke also stayed intact during all shaking experiments. However, a bit larger indentation (plastic deformation) was visible in the yoke, see Figure 11. In appendix D, a table with figures after each of the five shaking sets of ten shakes, has been added. The form of consent is added in Appendix C.

In Table 13, an overview of the results of all of the tests is given.

Figure 11. Front (left) and side (right) view of aluminium yoke and carbon fibre 3D printed yoke after the indicative experiment.

Table 13. Results experiments. When a specific requirement is not tested yet, NYR (not yet researched) is filled in.

			Knee	Elbow	Wrist	Ankle	Shoulder	Hip
Mechanical requirements	Allows 0-2 DOF movements (0 degrees for research to the actual influence of the movements)		1	1	2	2	2	2
	Adjustability of DOF and stiffness adjustability	0 DOF/ infinity stiffness in two directions	V	V	V	V	V	V
		1 DOF/ infinity stiffness in one direction	V	V	V	V	V	V
		2 DOF/ zero stiffness in two directions	NA	NA	V	V	V	V
	Adjustability of ROM within range of 0-3 year-olds	ROMs Flexion/Extension/ Abduction/Adduction	V/V	V/V	V/V/V/V	V/V/V/V	V/V/V/V (Flexion/ extension ROM is 2 degrees larger)	V/V/V/V (Flexion/ extension ROM is 2 degrees larger)
		Attachment piece necessary?	Yes, 15˚	Yes, 14˚	No	Yes, 10˚	No	No
Geometric requirements	Fixation of translations and rotations		V	V	V	V	V	V
	Add ability of demountable system		V	V	V	V	V	V
	Diameter smaller than 2.6 cm		Min ROM: X Max ROM: V	Min ROM: X Max ROM: V	Min ROM: X Max ROM: X	Min ROM: X Max ROM: X	Min ROM: V Max ROM: V	Min ROM: V Max ROM: V

		Knee	Elbow	Wrist	Ankle	Shoulder	Hip
General requirements	Modular and adjustable	V	V	V	V	V	V
	Safety and robustness (to what extended could be tested during the pilot experiment)	V	V	V	V	V	V
	No limited shelf life	NYR	NYR	NYR	NYR	NYR	NYR
	Easy to handle	NYR	NYR	NYR	NYR	NYR	NYR
	Partly re-useable	NYR	NYR	NYR	NYR	NYR	NYR
	Maintainable and repairable	NYR	NYR	NYR	NYR	NYR	NYR

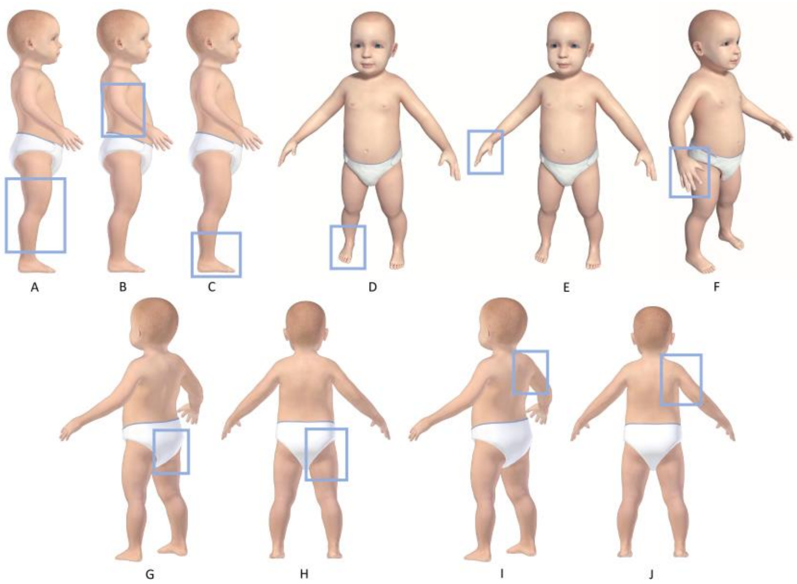
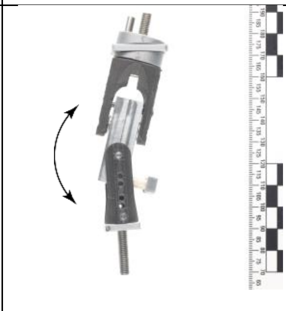
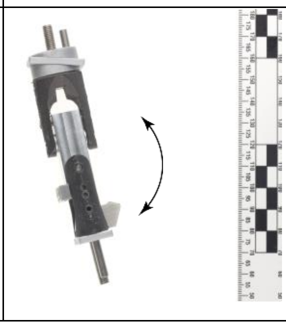
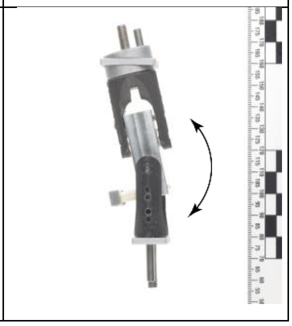


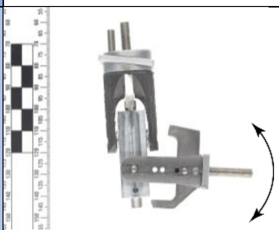
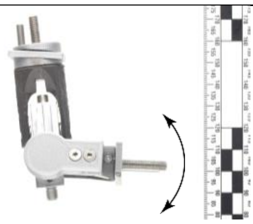
Figure 12. The viewpoints belonging to the pictures of the prototype of Table 14, Table 15 and Table 16.

Table 14. Photo's of the prototype of the knee and elbow in all extreme flexion/extension configurations for both the minimum and maximum ROMs. The viewpoint is added between brackets and explained in Figure 12.

	Knee		Elbow	
	Minimum (A)	Maximum (A)	Minimum (B)	Maximum (B)
Flexion				
Basis				

	Knee		Elbow	
	Minimum (A)	Maximum (A)	Minimum (B)	Maximum (B)
Extension				

Table 15. Photo's of the prototype of the ankle and wrist in all extreme flexion/extension/abduction (eversion)/adduction (inversion) configurations for both the minimum and maximum ROMs. The viewpoint is added between brackets and explained in Figure 12.

	Ankle		Wrist	
	Minimum (C)	Maximum (C)	Minimum (E)	Maximum (E)
Flexion				
Basis				
Extension				
	Minimum (D)	Maximum (D)	Minimum (F)	Maximum (F)
eversion/ abduction				

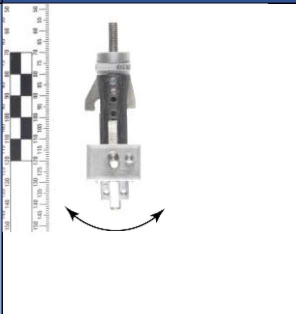
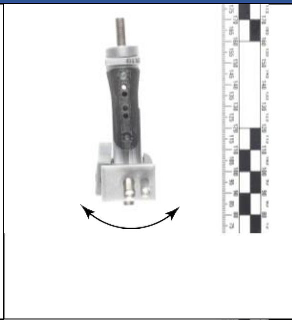
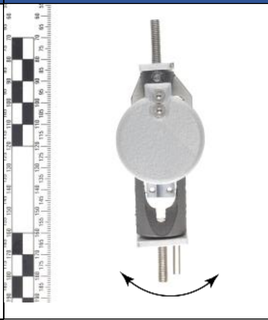
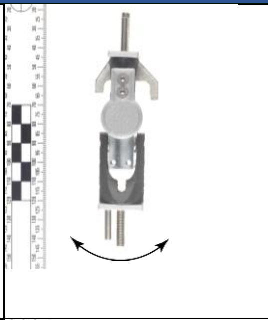
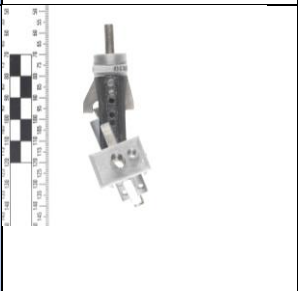
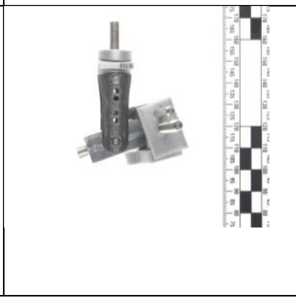
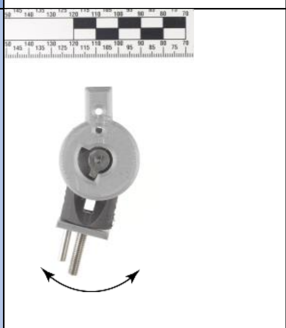
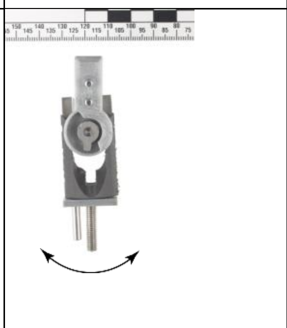
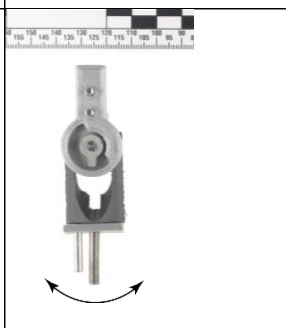
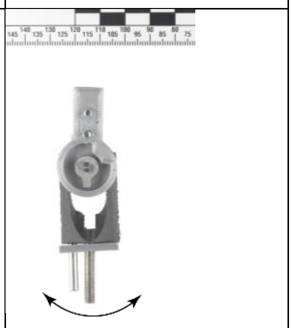
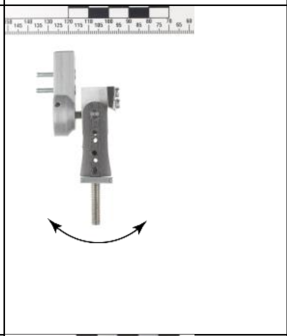
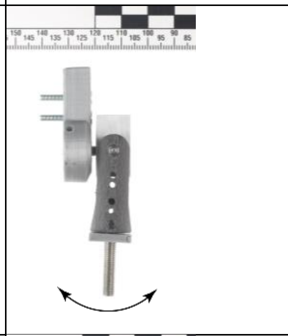
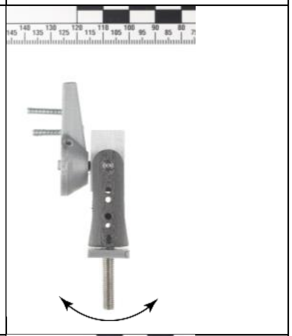
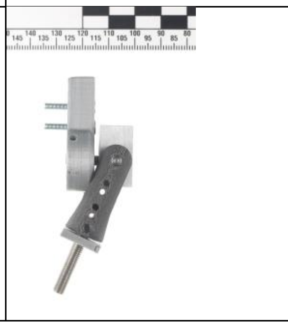
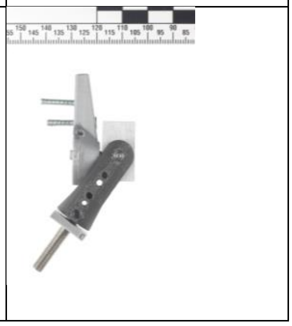
	Ankle		Wrist	
Basis				
inversion/ adduction				

Table 16. Photo's of the prototype of the hip and shoulder in all extreme flexion/extension/abduction/adduction configurations for both the minimum and maximum ROMs. The viewpoint is added between brackets and explained in Figure 12.

	Hip		Shoulder	
	Minimum (G)	Maximum (G)	Minimum (I)	Maximum (I)
Flexion				
Basis				
Extension				
	Minimum (H)	Maximum (H)	Minimum (J)	Maximum (J)

	Hip		Shoulder	
Abduction				
Basis				
Adduction				

Discussion

In this paper, research was performed to set up a requirements list for an anthropomorphic infant model for the age range 0-3 years. This model must be suitable for performing shake experiments and to analyse the kinematics and dynamics in the infant's body during these shaking movements. Furthermore a joint which could represent the ankle, wrist, knee and elbow and a joint representing the shoulder and hip was designed and a prototype was produced.

Overall requirements and design requirements for the major joints

One of the most important discussion points is the recency of the anthropomorphic data, presented in Table 3. The data was measured around 1975, by Snyder et al. (1977*)* [8]. Over the years the length of adult humans has been changed significantly [64]. Average men's length increased by around 2.1% and average woman's length increased by around 0.9%. This is possibly also true for infants. The length of the limbs, head, neck and torso are all very important for an accurate design of the doll in order to estimate the inertial properties of the infant's body. Therefore before designing the entire doll, research should be conducted to the contemporary size of the infant's body parts. Next to this phenomenon, the neck length must also be researched further, because this important data was lacking in the consulted sources. In this study this length was approximated by subtracting the head length by the shoulder to crown length. This is still an approximation due to the fact that the neck extends at the backside of the head. In future research, the focus can be laid on measuring the neck length of infants of various ages between 0-3 years old and taking into account the contemporary body size.

Some ROMs of joints and the neck have not yet been determined for infants, they are left blank in Table 4. In the case youngster, if present, or adult data was found, this data was presented. It is advised to perform further research to these ROMs, because ROMs can change very much between infants and youngsters or adults. Also ROMs of combined movements can be measured in future research, for instance the ROM of a leg in a combinational movement of abduction and flexion. Nowadays it is not known what the ROM in this combined position is, though it is a factor to consider as it has influence on the kinematics.

An accurate estimation of the stiffness of joints and neck for infants in the age range 0-3 years old is lacking. Only some adult data was found, presented in Table 4. In the designed joints, stiffness was not taken into account. This is based upon the assumption that infants don't brace themselves when they are being shaken, as well as the assumption that the passive stiffness is neglectable. Further research to these stiffnesses could be of added value to take into account the response of the infant body on shaking movements.

For building a realistic infant dummy, knowledge about collisions between the skull and both torso and shoulders is of added value, to take into consideration for the design of the dummy. This is due to the fact that the head of the infant can collide with the torso's upper front, backside or with the upper side of the shoulders, which means that the skull's motion suddenly stops. Due to their inertia, the internal structures can be damaged due to the fact that they move further, while the skull suddenly stops. In future studies, it is recommended to perform some impression tests on the shoulder, upper front and backside of the torso, in order to get an idea of the damping ratio's of these body parts. In this way these body parts can be simulated in a more realistic way in the test dummy.

Data about density, viscosity, elasticity and Poisson's ratio have been found and is presented for the CSF, eye tissue and brain tissue. For these variables it was not found if and how they vary within the age group of 0-3 years old. Furthermore data was lacking on elongation properties: ultimate stress and strain, yield stress and strain, elasticity and relaxation behaviour. Also their variations between 1 and 3 years old infants was not yet known. Only a rough indication of all these variables could be made. Therefore extra research to these properties is desirable, to take into account their influence in a realistic manner.

For the shear storage (describing the elastic behaviour) and loss moduli (describing the viscous behaviour), data of the brain was found of 5 and 12 months old infants. The question is if this data is representative for the entire age range of 0-3 years. The complex modulus has only been studied for adults. Therefore it can be researched in future work, if there are significant differences between the complex modulus of adults and 0-3 year olds.

Also the possible change in relaxation behaviour is not yet known and could be researched.

The brain volume of 3-year olds has not yet been found. This needs to be measured to be able to retrieve knowledge about the movements of the brain during shaking movements in infants in this age category.

All requirements the design must meet were subdivided into mechanical, geometric and general requirements. These requirements were set up, based on the information which was available in literature and based on personal assessment.

Design

To end up with a design, which fulfils the set up requirements the best, first a morphologic overview has been made of the most promising sub-designs fulfilling all separate requirements. These sub-designs are limited, they may not include all possible designs. Then these sub-designs were compared by the use of an Harris profile, in which the ranking was performed based on personal assessment.

The final design, was based on taking into account 2 DOF which is one of the most important discussion points of the final design. To allow for taking into account internal rotations of joints, an extra bearing could be added in line with the joint. In this way rotations of for instance bended knees and elbows could be integrated as well. These bended limbs could change the inertial properties of the total body, due to their relatively large mass. This could be the case during passive movements or during movements when infants do brace themselves when they are shaken, then bended elbow and bended knees could be of an influence when they rotate internal or external.

The prototype has now been made out of PLA, carbon fibre filled nylon, aluminium and stainless steel. In this design no ball bearings were used in the yokes, due to the lack of space available for them because of the relatively weakness of the carbon fibre filled nylon and the larger diameter of these bearings. Besides this, nylon already could perform as a good sliding bearing, being the second best solution. For the final product, it is advised to first further research the robustness and safety of these current materials and material combination, due to the fact that the combination of these materials give a lot of design freedom and are easy to produce allowing for the possibility to adjust them for case research considering specific infants.

If the prototype does fail during these robustness and safety experiments, the PLA and carbon fibre filled nylon parts could be made out of aluminium, with ball bearings. The stainless steel parts, will still be made out of this material, due to it's hardness, strength and the fact that this material does not rust. The aluminium parts will still be made out of aluminium, due to it's relatively small mass and its easy and accurate machinability.

During the design the add ability of sensors was kept in mind. There are possibilities in adding sensors on the outside or inside of the doll. Wireless sensors are most easy to use, but non-wireless sensors are also possible, if the electric wires are long enough to allow the joint to achieve the full ROM. During the design of the shoulder and hip, both rotational axis are designed to lay in the same point, this makes the movements easier to simulate. For the ankle, wrist, elbow and knee joint, this was not possible due to the extreme ROM of the ankle, therefore the axis did not lay in the same point. This is an important discussion point, because then it is less easy to simulate the movements. The sensors allow for performing measurements on for instance the bridging veins stress and strain, to give an indication of their values during shaking movements.

Joint tests

During this research, the mechanical and geometric requirements and to a limited extend some general requirements (modularity, adjustability, safety and robustness) could be tested with the SolidWorks model and prototype. In future research, also the other general requirements could be researched: limited shelf life, easy to handle, re-useability, maintainability and repairability. Next to that more extensive experiments to safety and robustness of the design, could be executed, resulting in a more reliable outcome.

The mechanical requirements were tested by the use of the SolidWorks model and the prototype and were all achieved. Only 2 degrees larger ROM ere measured for the flexion/extension in the hip and shoulder. Therefore for the production of the joint, it is advised to use the wire EDM technique for cutting the limiter of the shoulder and hip, due to the fact that this technique is more precise and leads to more precise ROMs compared to the laser cutting technique.

The geometric requirements were partly achieved, specifically the maximum diameter was exceeded. The joint with the limiters is sometimes broader than the smallest wrist dimension (a few millimeters difference). The general requirements were partly tested. It was noted that the two models were modular and adjustable to all joints. The safety and robustness were tested to a limited extend by the conduction of an indicative pilot study.

In this study the safety and robustness were tested by checking if the design could handle the impact on the limiters. The impact depends on two variables: the force applied on the system by the participant to stop the momentum of the mass, and the impact moment, build up by the mass during the shaking movement.

Two possible shaking situations are shown in Figure 13, situation A represents the situation in which the weight is caught underhand, situation B is the situation in which the stopping moment is applied from above. Both situations are represented by considering the moment right before impact and the moment just after impact.

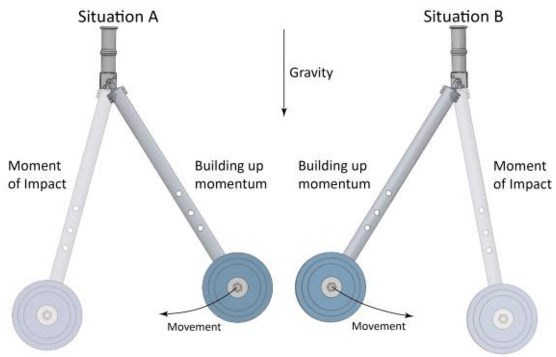


Figure 13. Shaking situations during the experiment, on the left side situation A and on the right side situation B. Situation A represents the situation when the weight is caught underhand, situation B represents the situation in which the stopping moment is applied from above.

The situation of the experiment can be best described by applying the laws of conservation of momentum and energy for before and after the 'collision':

$$\frac{1}{2} * m * v^2 = F_{mean} * \Delta x$$

$$m * v = F_{mean} * \Delta t$$

Here, m is the mass of the weights (representing the infant's mass), v the velocity of the weights right before impact, F the mean effective force on the system for catching the momentum (primarily delivered by the participant) and Δt and Δx the time and distance it takes for the participant to stop the mass to standstill. So for example, in situation A, Δx is the distance the handle moves to the left during stopping the movement of the weights.

In situation B, force F is higher compared to situation A, because it's in the direction of gravity, therefore Δx and Δt are lower and thus in situation B, the impact on the system will be higher. Likewise, in situation B the participant is observed to be able to build up a bit momentum as well. This momentum, primarily consisting of his arm, is in opposite direction of the (impact) momentum of the weights, results in a higher stopping force and thus lower Δx and Δt, yielding larger impact on the system.

The actual maximum force on the system, applied by the pins on the upstanding edges of the yoke, is magnitudes higher than the maximum force of the participant, because the distance of the blocking pin to the point of rotation (a) is much shorter than the distance of the participants hold to the point of rotation (b), as shown in Figure 14.

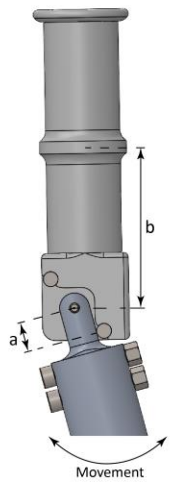


Figure 14. Overview of moment arms of handle and design at the moment of impact.

In the aluminium yoke, two very small dents were visible after the shaking tests. No critical damage was seen. In the carbon fibre 3D printed yoke, a bit larger dents were visible. This printed yoke, further stayed in tact, which gives hope to future research to this material. This material namely allows for easy producibility and adjustability.

It is advised for future research to repeat the test as described in the method section with more participants, to be able to draw more confident conclusions about the strength of the design. Next to that, further research to the most extreme shaking setting needs to be performed. During this pilot shaking test, it was experienced that the hand of a 0-3 years old infant is very small and could not be held very firmly. When the underarm as a whole can be held, maybe an even larger impact could be inflicted on the design, by stopping the swing faster due to holding the arm more firmly with two hands.

Also this indicative mechanical shake test could be repeated for the shoulder and hip design, in which a smaller distance between the pins and the design was present.

Another advised future study option which could be performed is research to the possibilities of the carbon fibre filled nylon model. In this study it was tested with impacts onto a plastic block. But maybe the limiters could also be made from this nylon material. Or, if the limiters will be of stainless steel, it could be researched if the nylon print stays intact even when impacts occur on these stainless steel pins. This material is very interesting, due to the promising possibilities it gives on the design freedom and ease for producing more parts. Next to that the production time is short.

Conclusion

This research took place as part of a larger research to develop a new physical model of an infant's body, to allow for case-specific research to the infant's body reaction caused by shaking movements.
The goal of this particular research was to set up a requirements list of an anthropomorphic infant model (applicable for case-specific research in the age range of 0-3 years) and to design, produce and test joints for that infant model.

An extensive list of the requirements of the anthropomorphic shake doll has been developed. Nevertheless, some crucial information is still lacking in the literature. Examples of such information is recent data of the dimensions of the limbs, head, neck and torso of infants of 0-3 years old and some lacking ROMs of infants. Another important topic for future research is the tensioning of the muscles of infants when being shaken.

Two designs were made for the two groups of joints (group 1: knee, elbow, ankle and wrist, group 2: hip and shoulder), due to the fact that the ROMs of these two groups were not compatible. For all joints, addable limiters for representing the minimum and maximum ROMs were made as well. The ankle, knee, wrist and elbow design was tested in an indicative mechanical shake test in which the structural integrity of the design was checked under influence of shaking movements. It was found that the aluminium design stayed completely intact during the experiments. Only some very small dents at the impact locations were noted. Besides this, a small indicative mechanical shake test was performed with the yoke made from carbon fiber filled nylon and impacts against a plastic block. Dents were visible after the test at the locations of impact, but the design didn't fail. Extra research on this material is advised as it makes production more easy and allows for more design freedom through its related 3D printing techniques.

In short, both goals of this study were partly achieved. The requirements list was set up, though some crucial data was lacking in the literature. Likewise, the design goal was also met partly. The designs were finished, but more testing is necessary as only one indicative mechanical pilot study was performed.

All mechanical requirements, and testable general requirements were met (safety, robustness, modularity and adjustability), but the geometric requirements were partly achieved (the max diameter of the system was a few millimeters too big). Other general requirements that still need to be tested: thoroughly safety and robustness, limited shelf life, easy to handle, maintainable and repairable.

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References

1. Surgeons, A.A.o.N. *Shaken Baby Syndrome*. [cited 2021 10-7]; Available from: https://www.aans.org/en/Patients/Neurosurgical-Conditions-and-Treatments/Shaken-Baby-Syndrome.
2. karst, W., *Personal Communication*. 2019: The Hague, NFI.
3. Keenan, H.T., et al., *A Population-Based Study of Inflicted Traumatic Brain Injury in Young Children.* JAMA, 2003. **290**(5): p. 621-626.
4. Syndrome, N.C.o.S.B. *The Period of Purple Crying*. [Website] [cited 2021 26 feb]; Available from: https://www.dontshake.org/purple-crying.
5. Ryall, L., *Personal email communication*. 2020.
6. Tatiana, *Personal email communication*. 2020.
7. Schneider, L.W., et al. *SIZE AND SHAPE OF THE HEAD AND NECK FROM BIRTH TO FOUR YEARS. FINAL REPORT*. 1986.
8. Snyder, R.G., *Anthropometry of Infants, Children, and Youths to Age 18 for Product Safety Design. Final Report [microform] / Richard G. Snyder and Others*, ed. A.A.H.S.R.I. Michigan Univ. 1977, [Washington, D.C.]: Distributed by ERIC Clearinghouse.
9. De Jager, K., *Personal Communication*. 2020.
10. Waagmeester, K., *Personal Communication*. 2020.
11. Wismans, J., et al., *Q-dummies report: advanced child dummies and injury criteria for frontal impact*. 2008, European Enhanced Vehicle-safety Committee.
12. Jager, K., et al., *Assessing new child dummies and criteria for assessment of child occupant*. 2005.
13. Cory, C.Z. and B.M. Jones, *Can shaking alone cause fatal brain injury? A biomechanical assessment of the Duhaime shaken baby syndrome model.* Med Sci Law, 2003. **43**(4): p. 317-33.
14. Duhaime, A.C., et al., *The shaken baby syndrome. A clinical, pathological, and biomechanical study.* J Neurosurg, 1987. **66**(3): p. 409-15.
15. van Haaster, R.M.H.P., *A combined generator for child multibody models*, in *DCT rapporten*. 1995, Technische Universiteit Eindhoven: Eindhoven.
16. Jensen, R.K., *Changes in segment inertia proportions between 4 and 20 years.* Journal of Biomechanics, 1989. **22**(6): p. 529-536.
17. TNO, *Groeidiagram 0-4 jaar jongens NL*. 2010, TNO.
18. TNO, *Groeidiagram 0-4 jaar meisjes NL*. 2010, TNO.
19. van Zandwijk, J.P., et al., *Modeling of inflicted head injury by shaking trauma in children: what can we learn?* Forensic Science, Medicine and Pathology, 2019. **15**(3): p. 423-436.
20. Priester, M. 2020.
21. De Lange, K., 2020.
22. Schuenke, M., *Thieme atlas of anatomy. General anatomy and musculoskeletal system*. 2nd edition, Latin nomenclature. ed. General anatomy and musculoskeletal system, ed. E. Schulte, et al. 2015, New York, NY: Thieme.
23. Reese, N.B., *Joint range of motion and muscle length testing*. 2nd ed ed, ed. W.D. Bandy. 2010, St. Louis, MI: Saunders.
24. van Empelen, R., R.N. der Sanden, and A. Hartman, *Kinderfysiotherapie*. 2017: Bohn Stafleu van Loghum.
25. Sakka, L., G. Coll, and J. Chazal, *Anatomy and physiology of cerebrospinal fluid.* European Annals of Otorhinolaryngology, Head and Neck Diseases, 2011. **128**(6): p. 309-316.
26. Lui, A.C.P., T.Z. Polis, and N.J. Cicutti, *Densities of cerebrospinal fluid and spinal anaesthetic solutions in surgical patients at body temperature.* Canadian Journal of Anaesthesia, 1998. **45**(4): p. 297.
27. Bloomfield, I.G., I.H. Johnston, and L.E. Bilston, *Effects of Proteins, Blood Cells and Glucose on the Viscosity of*

Cerebrospinal Fluid. Pediatric Neurosurgery, 1998. **28**(5): p. 246-251.
28. Sampaolesi, R.Z., J.; Sampaolesi, J.R., *Normal Intraocular Pressure in Children from Birth to Five Years of Age*, in *The Glaucomas: Volume I - Pediatric Glaucomas*, R. Sampaolesi, J.R. Sampaolesi, and J. Zárate, Editors. 2009, Springer Berlin Heidelberg: Berlin, Heidelberg.
29. Yamazaki, J., M. Yoshida, and H. Mizunuma, *Experimental analyses of the retinal and subretinal haemorrhages accompanied by shaken baby syndrome/abusive head trauma using a dummy doll.* Injury, 2014. **45**(8): p. 1196-1206.
30. Kim, H.G., et al., *Ultrasound elastography of the neonatal brain: Preliminary study* Journal of Ultrasound in Medicine, 2017. **36**(7): p. 1313-1319.
31. Blom, E.A., *The mechanical and material properties of brain and bridging veins of infants and a comparison to simulant materials - A systematic review*. 2020, TU Delft: Delft.
32. Finan, J.D., et al., *Regional mechanical properties of human brain tissue for computational models of traumatic brain injury.* Acta Biomaterialia, 2017. **55**: p. 333-339.
33. Lipps, D.B., et al., *Quantifying the Multidimensional Impedance of the Shoulder During Volitional Contractions.* Annals of Biomedical Engineering, 2020. **48**(9): p. 2354-2369.
34. Carvalhais, V.O.d.C., et al., *Validity and reliability of clinical tests for assessing hip passive stiffness.* Manual Therapy, 2011. **16**(3): p. 240-245.
35. Chleboun, G.S., et al., *The relationship between elbow flexor volume and angular stiffness at the elbow.* Clinical Biomechanics, 1997. **12**(6): p. 383-392.
36. Formica, D., et al., *The passive stiffness of the wrist and forearm.* Journal of neurophysiology, 2012. **108**: p. 1158-66.
37. McHugh, M. and D. Hogan, *Effect of knee flexion on active joint stiffness.* Acta physiologica Scandinavica, 2004. **180**: p. 249-54.
38. Staheli, L.T., et al., *Lower-extremity rotational problems in children. Normal values to guide management.* J Bone Joint Surg Am, 1985. **67**(1): p. 39-47.
39. Park, H.S., N.A. Wilson, and L.Q. Zhang, *Gender differences in passive knee biomechanical properties in tibial rotation.* J Orthop Res, 2008. **26**(7): p. 937-44.
40. Roy, A., et al., *Measurement of passive ankle stiffness in subjects with chronic hemiparesis using a novel ankle robot.* Journal of neurophysiology, 2011. **105**(5): p. 2132-2149.
41. Drews, J., J. Vraciu, and G. Pellino, *Range of Motion of the Joints of the Lower Extremities of Newborns.* Physical & Occupational Therapy in Pediatrics, 2009. **4**: p. 49-63.
42. McGill, S.M., et al., *Passive stiffness of the human neck in flexion, extension, and lateral bending.* Clinical Biomechanics, 1994. **9**(3): p. 193-198.
43. Öhman, A. and E. Beckung, *Reference Values for Range of Motion and Muscle Function of the Neck in Infants.* Pediatric Physical Therapy, 2008. **20**: p. 53-58.
44. Dugailly, P.M., et al., *Assessment of cervical stiffness in axial rotation among chronic neck pain patients: A trial in the framework of a non-manipulative osteopathic management.* Clinical Biomechanics, 2018. **53**: p. 65-71.
45. De Bruijn, E., F. van der Helm, and R. Happee, *Analysis of isometric cervical strength with a nonlinear musculoskeletal model with 48 degrees of freedom.* Multibody System Dynamics, 2015. **34**: p. 1-24.
46. Moroney, S.P., et al., *Load-displacement properties of lower cervical spine motion segments.* J Biomech, 1988. **21**(9): p. 769-79.
47. Pintar, F.A., *Biomechanical Properties of the Human Intervertebral Disk in*

Tension. ASME Adv Bioeng, New York, NY. 1986, 1986.
48. De Jager, M.K.J., *Mathematical head-neck models for acceleration impacts.* 1998.
49. Eberlein, R., M. Frohlich, and E.J.C.M.f.R. Hasler, *Finite-element-analyses of intervertebral discs: Recent advances in constitutive modelling.* 1999. **1**: p. 221.
50. McGill, S., J. Seguin, and G. Bennett, *Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding.* Spine (Phila Pa 1976), 1994. **19**(6): p. 696-704.
51. Watanabe, H., et al., *[The range of joint motions of the extremities in healthy Japanese people--the difference according to the age (author's transl)].* Nihon Seikeigeka Gakkai Zasshi, 1979. **53**(3): p. 275-61.
52. Boone, D.C., et al., *Reliability of Goniometric Measurements.* Physical Therapy, 1978. **58**(11): p. 1355-1360.
53. Schneider, K. and R.F. Zernicke, *Mass, center of mass, and moment of inertia estimates for infant limb segments.* Journal of Biomechanics, 1992. **25**(2): p. 145-148.
54. Ocstard, *Baby - Rigged 3D model*. 2017, Turbosquid.
55. Pasquesi, S.A. and S.S. Margulies, *Failure and Fatigue Properties of Immature Human and Porcine Parasagittal Bridging Veins.* Annals of Biomedical Engineering, 2017. **45**(8): p. 1877-1889.
56. Shukla, V., *FEA Investigation of a Human Eye Model Subjected To Intra-Ocular Pressure (IOP) and External Pressure.* Journal of Mechanical Engineering and Applied Mechanics, 2017. **2**: p. 1-14.
57. Knickmeyer, R.C., et al., *A structural MRI study of human brain development from birth to 2 years.* J Neurosci, 2008. **28**(47): p. 12176-82.
58. Chatelin, S., et al., *Towards child versus adult brain mechanical properties.* Journal of the Mechanical Behavior of Biomedical Materials, 2012. **6**: p. 166-173.
59. Yeung, J., et al., *Paediatric brain tissue properties measured with magnetic resonance elastography.* Biomechanics and Modeling in Mechanobiology, 2019. **18**(5): p. 1497-1505.
60. McIlvain, G., et al., *Mechanical properties of the in vivo adolescent human brain.* Developmental Cognitive Neuroscience, 2018. **34**: p. 27-33.
61. Qiu, C. and J.S. Dai, *Introduction*, in *Analysis and Synthesis of Compliant Parallel Mechanisms—Screw Theory Approach*, C. Qiu and J.S. Dai, Editors. 2021, Springer International Publishing: Cham. p. 1-15.
62. Bayani, S., R. Rastegari, and F. Samavati, *Design of Hyper Redundant Robot using Ball screw Mechanism Approach*. 2015.
63. Weerakkody, Y.D., A. *Ball and socket joint.* [cited 2021 28-08-2021]; Available from: https://radiopaedia.org/articles/ball-and-socket-joint.
64. CBS. *Lichaamsgroei 1981-2018*. 27-11-2019; Available from: https://www.cbs.nl/nl-nl/nieuws/2019/48/lichaamsgroei-1981-2018-recent-vooral-gewichtstoename.

Appendix A

Extensive overview of all Modelling requirements for the sensor equipped anthropomorphic doll.

General requirements

0. The requirements the doll needs to meet are:
   - The doll should be modular and adjustable in order to be able to:
     i. represent children of various builds,
     ii. allow for measuring rigid body behaviour and behaviour of internal structures,
     iii. allow for replacing or adjusting relevant parts to vary degrees of freedom (DOF), range of motion and passive stiffness,

     while minimizing the extent to which measurement electronics have to be replaced, adjusted or recalibrated.

   - The doll should:
     i. be safe to use,
     ii. have no limited shelf life,
     iii. be easy to handle,
     iv. be partly re-useable,
     v. be easy to maintain and repair,
     vi. be easy changeable and adjustable,
     vii. be robust.

1. Torso dynamics
   To enable exposing the doll to realistic shaking movements, the doll needs to allow for the following:
   - Requirements for geometry and mechanics
     i. <u>Available information on geometry and mechanics</u>
     ii. <u>Yet to be determined</u>
     iii. <u>Assumptions</u>
     iv. <u>Working requirements</u>

     All of these four subchapters contain the following subjects related to the torso and limbs:

       - **Anthropomorphic dimensions**
       - **DOF** of joints
       - **ROM** of joints
       - Joint **stiffness**
       - **Inertial properties**

   - Measurement requirements
     i. <u>What to measure</u> (variables, directions):
        Positions, velocities and accelerations of the torso in the shaking direction.
     ii. <u>How to measure</u> (accuracy, resolution, range):
        TBD

   - Usability requirements
     i. <u>Replaceable parts:</u>
        - Limbs
     ii. <u>Adaptable parts:</u>
        - Dimensions and mass of torso
        - DOF, ROM and stiffness of joints

2. Torso-skull transfer
   To enable realistic simulation of the kinematics and dynamics of the neck, in order to transfer the torso's movements to the head in a realistic way, the following requirements must be met:
   - Requirements for geometry and mechanics
     i. <u>Available information on geometry and mechanics</u>
     ii. <u>Yet to be determined</u>
     iii. <u>Assumptions</u>

iv. Working requirements

All four subchapters contain the following subjects related to the neck:

- **Anthropomorphic dimensions**
- **DOF**
- **ROM**
- Neck **stiffness**
- **Collision** torso and skull

- Measurement requirements
  i. What to measure (variables, directions):
  Stress in the neck and the forces applied onto the vertebrae.
  ii. How to measure (accuracy, resolution, range):
  TBD

- Usability requirements
  i. Replaceable parts:
  - Neck
  ii. Adaptable parts:
  - DOF, ROM and stiffness of neck

3. Skull dynamics

To enable realistic dynamical movements, the following requirements must be met:

- Requirements for geometry and mechanics
  i. Available information on geometry and mechanics
  ii. Yet to be determined
  iii. Assumptions
  iv. Working requirements

All four subchapters contain the following subjects related to the skull:

- **Anthropomorphic dimensions**
- **Inertial properties**

- Measurement requirements
  i. What to measure (variables, directions):
  Positions, velocities and accelerations of the skull in various directions.
  ii. How to measure (accuracy, resolution, range):
  TBD

- Usability requirements
  i. Replaceable parts:
  - Skull
  ii. Adaptable parts: None

4. Skull-internal transfer

To allow for a realistic transfer of forces and movements from the skull to the brain, the following requirements must be met:

- Requirements for geometry and mechanics
  i. Available information on geometry and mechanics
  ii. Yet to be determined
  iii. Assumptions
  iv. Working requirements

All four subchapters contain the following subjects:

- **CSF** properties
- **Bridging veins** elongation properties
- **Eye** properties

- Measurement requirements
    i. What to measure (variables, directions):
       Internal interactions and pressures.
    ii. How to measure (accuracy, resolution, range):
       TBD

- Usability requirements
    i. Replaceable parts:
        - Material of fluids/internal anatomical structures: CSF, brain, bridging veins and eyes
    ii. Adaptable parts: None

5. Internal dynamics

   To allow for realistic internal dynamics, the following requirements must be met:

- Requirements for geometry and mechanics
    i. Available information on geometry and mechanics
    ii. Yet to be determined
    iii. Assumptions
    iv. Working requirements

  All four subchapters are focused on the brain.

- Measurement requirements
    i. What to measure (variables, directions):
       The movements/velocities/accelerations of the brain.
    ii. How to measure (accuracy, resolution, range):
       TBD

- Usability requirements
    i. Replaceable parts:
        - Material of brain
    i. Adaptable parts: None

Elaboration on general requirements

0. The requirements the doll needs to meet are:

- The doll should be modular and adjustable in order to be able to:
  i. represent children of various builds in the age range of 0-3 years,
  ii. allow for measuring rigid body behaviour as well as the behaviour of relevant internal anatomical structures,
  iii. allow for replacing or adjusting relevant parts to vary degrees of freedom (DOF), range of motion (ROM) and stiffness,

  while minimizing the extent to which measurement electronics, electronics which measure the positions, velocities and accelerations of internal tissue and rigid bodies, have to be replaced, adjusted or recalibrated.

- The doll should:
  i. be safe to use, it does not loose parts while being shaken by either a person or a shaking machine,
  ii. have no limited shelf life, when stored the model must remain suitable for shaking experiments,
  iii. be easy to handle, it should be clear how the model works and how it needs to be assembled,
  iv. be partly re-useable, the basic structure of the torso, the limbs, the skull and the neck need to be re-useable while the structures inside the head does not need to be re-useable,
  v. be easy to maintain and repair (due to the modularity of the doll),
  vi. be easy changeable and adjustable, the limbs, neck and head are easy to change and the torso is easy to adjust,
  vii. be robust, it needs to stay intact during the shaking experiments.

1. Torso dynamics

To enable exposing the doll to realistic shaking movements, the doll needs to allow for the following:

- Requirements for geometry and mechanics

  A human should be able to shake, with realistic efforts, the doll with a realistic motion. This includes a realistic velocity, acceleration and force. A model including limbs will allow for more realistic torso motions.
  This will require realistic torso and limbs, meaning realistic anthropomorphic dimensions, DOF, ROM, joint stiffness and inertial properties.

  i. <u>Available information on geometry and mechanics</u>
     - **Anthropomorphic dimensions**: presented in Appendix A.1, Table 1 and Table 2. The last table is more recent than the first table.
     - **DOF** of joints: presented in Appendix A.2, Table 1.
     - **ROM** of joints: presented in Appendix A.2, Table 1.
     - Joint **stiffness**: presented in Appendix A.2, Table 1 (adult data).
     - **Inertial properties**: segmental masses are presented Appendix A.4, Table 1 and Table 2, segmental dimensions are presented in Appendix A.1, Table 1 and Table 2, segmental radius of gyration and segmental inertias are presented in Appendix A.5., Table 1 and Table 2, and the locations of the centre of mass are presented in Appendix A.6, Table 1.

ii. Yet to be determined

- **Anthropomorphic dimensions**: None
- **DOF** of joints: None
- **ROM** of joints: In Appendix A.2, Table 1, entries left blank are yet to be determined. (important due to the large differences of the ROM's between infants and adults when looking at the ROM's of movements in which both were available)
- Joint **stiffness**: In Appendix A.2, Table 1, entries left blank are yet to be determined (adult data), besides this the joint stiffness of infants needs to be determined. (important due to the fact that limited is known about this stiffness and may vary significantly for infants when compared to adults)
- **Inertial properties**: The exact inertial properties of the limbs, taking into account not only the rotations around one transversal axis, but also around the other axis around which the limbs move during shaking. The exact inertial properties of the torso, now only one transversal axis is taken into account (around the horizontal axis through the shoulder).
  (for the limbs a good estimation could be made based upon this one transversal axis due to their connection to the torso, but for the torso a better estimation is necessary due to the fact that it does not rotate mainly around the transversal shoulder axis)
  The exact possible changes of the position of the centre of mass.
  (the current values already give a sufficient indication of this position, due to the fact that it did not change significantly during the first 1.5 years of life, therefore it seems that it also does not change significantly between 1.5 and 3.0 years of life)

iii. Assumptions

- **Anthropomorphic dimensions**:
  The dimensions of the babies, which will be researched with this model in case-specific research, are assumed to be similar to the dimensions presented in in Appendix A.1, Table 1 and Table 2.
  It is assumed that the length of the torso could be determined by subtraction of the shoulder to head length from the crown-rump length.
- **DOF** of joints:
  None
- **ROM** of joints:
  Infants have similar ROM as youngsters and adults, this is assumed when no ROM of infants was available.
- Joint **stiffness**:
  The joint stiffness of infants is assumed to be similar to the stiffness of joints of adults.
- **Inertial properties**:
  The inertial properties of the limbs and torso are presented for the most relevant rotation (basically assuming that limbs only rotate around one axis while realistically there may be more).
  The regression line coefficients used to calculate the values in Appendix A.4 and Appendix A.5. were suitable for use in the age range of 0-3 years, based on tests and analysations of TNO [3, 4]
  No significant changes in centre of mass positions, presented in percentages, at limbs were visible during the first 1.5 years of age [5]. It is assumed that in between 1.5 and 3 years of age this relative location does not change significantly as well.

iv. Working requirements

- **Anthropomorphic dimensions** (Appendix A.1, Table 1 and Table 2)
  - Minimum: the dimensions of the torso and limbs of the model fall within the minimum values (values of the youngest infants) and maximum values (values of the oldest infants).
  - Desired: the dimensions of the torso and limbs of the model fall within the minimum and maximum values of the dimensions for each age category.
  - Ideal: the dimensions of the torso and limbs of the model are adjustable within the range of the youngest to the oldest infants.
- **DOF** of joints: the working requirements are presented in Appendix A.3, Table 1.
- **ROM** of joints: the working requirements are presented in Appendix A.3, Table 1.
- Joint **stiffness**: the working requirements are presented in Appendix A.3, Table 2.
- **Inertial properties** (Appendix A.1: Table 1 and Table 2, Appendix A.4, Table 1 and Table 2, Appendix A.5., Table 1 and Table 2, Appendix A.6, Table 1):
  - Minimum: the values for the dimensions, segmental mass, segmental radius of gyration, segmental inertia and location of mass centre fall within the minimum values (values of the youngest infants) and maximum values (values of the oldest infants).
  - Desired: the values for the dimensions, segmental mass, segmental radius of gyration, segmental inertia and location of mass centre are similar as given for each age category.
  - Ideal: the dimensions, segmental mass, segmental radius of gyration, segmental inertia and location of mass centre are adjustable within the range of the youngest to the oldest infants.

o Measurement requirements

i. What to measure (variables, directions):

- Variables of the torso
  - Minimum, desired and ideal: The positions, velocities and accelerations of the torso of the model during shaking. The direction in which will be measured is similar as the shaking direction.

ii. How to measure (accuracy, resolution, range):

TBD

o Usability requirements

ii. Replaceable parts:

- Limbs, to limbs with different dimensions and mass

iii. Adaptable parts:

- Dimensions and mass of torso
- DOF, ROM and stiffness of joints

2. Torso-skull transfer

To enable realistic simulation of the kinematics and dynamics of the neck, in order to transfer the torso's movements to the head in a realistic way, the following requirements must be met:

- Requirements for geometry and mechanics

  To allow for realistic kinematics and dynamics in the neck, realistic anthropomorphic dimensions, DOF, ROM, neck stiffness are indispensable. Also, the damping of the collision between the skull and the torso needs to be realistic.

i. Available information on geometry and mechanics
   - **Anthropomorphic dimensions**: presented in Appendix A.1, Table 1 and Table 2. The last table focuses more onto the head and neck and is more recent than the first table, which is more focused onto the torso and limbs.
   - **DOF**: presented in Appendix A.2, Table 1.
   - **ROM**: presented in Appendix A.2, Table 1.
   - Neck **stiffness**: presented in Appendix A.2, Table 1 (adult data).
   - **Collision** torso and skull: No available information.

ii. Yet to be determined
   - **Anthropomorphic dimensions**: The neck length of infants. (important due to the fact that e.g. when calculating the inertial properties of only the head, this neck length is necessary to be known, besides that the neck length is indispensable for analysing the exact skull positions during shaking)
   - **DOF**: None
   - **ROM**: In Appendix A.2, Table 1, entries left blank are yet to be determined. (important due to the large differences of the ROM's between infants and adults when looking at the ROM's of movements in which both were available)
   - Neck **stiffness**: In Appendix A.2, Table 1, entries left blank are yet to be determined (adult data). Besides this the neck stiffness of infants need to be determined. (important due to the fact that limited is known about this stiffness and may vary significantly for infants when compared to adults)
   - **Collision** torso and skull: The damping of the chin, left & right side of the skull and backside of the skull which collides with the torso's upper front & backside and the upper side of the shoulders.
     (important due to the fact that this damping could have influence onto the movements of the structures inside the skull)

iii. Assumptions
   - **Anthropomorphic dimensions**: The neck length is assumed as the length when subtracting the head height from the shoulder to head length.
   - **DOF**: None
   - **ROM**:
     Infants have similar ROM as youngsters and adults, this is assumed when no ROM of infants was available.
   - Neck **stiffness**:
     The neck stiffness of infants is similar to the stiffness of adults.
   - **Collision** torso and skull: None

iv. Working requirements
   - **Anthropomorphic dimensions** (Appendix A.1, Table 1 and Table 2):

    - Minimum: the dimensions of the neck of the model fall within the minimum values (values of the youngest infants) and maximum values (values of the oldest infants).
    - Desired: the dimensions of the neck of the model are similar as given for each age category.
    - Ideal: the dimensions of neck of the model are adjustable within the range of the youngest to the oldest infants..
- **DOF**: the working requirements are presented in Appendix A.3, Table 1.
- **ROM**: the working requirements are presented in Appendix A.3, Table 1.
- Neck **stiffness**: the working requirements are presented in Appendix A.3, Table 2.
- **Collision** torso and skull:
    - Minimum: the material of the chin, left and right side of the skull, backside of the skull, upper front- and backside of the torso and upper-side of the shoulders is interchangeable.
    - Desired: the material of the chin, left and right side of the skull, backside of the skull, upper front- and backside of the torso and upper-side of the shoulders is interchangeable and has similar damping properties as human material.
    - Ideal: the material of the chin, left and right side of the skull, backside of the skull, upper front- and backside of the torso and upper-side of the shoulders is interchangeable and has similar damping properties as real infants material.

- Measurement requirements
    i. <u>What to measure</u> (variables, directions):
        - Variables of the neck
            - Minimum, desired and ideal: Stress in the neck and the forces applied onto the vertebrae.
    ii. <u>How to measure</u> (accuracy, resolution, range):
    TBD

- Usability requirements
    i. <u>Replaceable parts:</u>
        - Neck, to a neck with different dimensions
    ii. <u>Adaptable parts:</u>
        - DOF, ROM and stiffness of neck

3. Skull dynamics

To enable realistic dynamical movements, the following requirements must be met:

- Requirements for geometry and mechanics

  i. Available information on geometry and mechanics

  - **Anthropomorphic dimensions**: presented in Appendix A.1, Table 1 and Table 2. The last table focuses more onto the head and neck and is more recent than the first table, which is more focused onto the torso and limbs.
  - **Inertial properties**: the segmental masses are presented in Appendix A.4, Table 1 and Table 2, the segmental dimensions are presented in Appendix A.1, Table 1 and Table 2, the proportional segmental radius of gyration and segmental inertias of the combination of skull and neck are presented in Appendix A.5., Table 1 and Table 2.

  ii. Yet to be determined

  - **Anthropomorphic dimensions**: None
  - **Inertial properties**: the exact location of centre of mass of the skull. (it can be estimated that the centre of mass will be located approximately in the middle of the skull, due to the fact that the total skull is filled with similar materials on all sides). For the exact inertial properties of the skull (incl. neck), now only one transversal axis is taken into account (around the horizontal axis through the shoulder). (important due to the fact that the other rotations around other axis have influence onto the movements of the internal structures inside the skull)

  iii. Assumptions

  - **Anthropomorphic dimensions**: The skull dimensions of the babies which will be researched in case-specific research with this model are similar to the dimensions presented in Appendix A.1, Table 1 and Table 2.
  - **Inertial properties:** The regression line coefficients used to calculate the values were suitable for use in the age range of 0-3 years, based on tests and analysations of TNO [3, 4]. The inertial properties of the skull (incl. neck) are presented for rotation around one transversal axis, which is assumed to be the most important rotation in which the inertial properties play a role.

  iv. Working requirements

  - **Anthropomorphic dimensions** (Appendix A.1, Table 1 and Table 2)
    - Minimum: the dimensions of the skull of the model fall within the minimum values (values of the youngest infants) and maximum values (values of the oldest infants).
    - Desired: the dimensions of the skull of the model are similar as given for each age category.
    - Ideal: the dimensions of the skull of the model are adjustable within the range of the youngest to the oldest infants.
  - **Inertial properties** (Appendix A.1, Table 1, Table 2, Appendix A.4, Table 1 and Table 2, Appendix A.5., Table 1 and Table 2):
    - Minimum: the values for the dimensions, segmental mass, proportional segmental radius of gyration and segmental inertia fall within the minimum values (values of the youngest infants) and maximum values (values of the oldest infants).
    - Desired: the values for the dimensions, segmental mass, the proportional segmental radius of gyration and segmental inertia are similar as given for each age category.

- Ideal: the dimensions, segmental mass, the proportional segmental radius of gyration and segmental inertia are adjustable within the range of the youngest to the oldest infants.

- Measurement requirements
  i. What to measure (variables, directions):
     - Variables of the skull
       - Minimum, desired and ideal: Positions, velocities and accelerations of the skull in the directions determined by Lateral flexion of the neck, Flexion/ Extension of the neck and Axial rotation of the neck.
  ii. How to measure (accuracy, resolution, range):
     TBD

- Usability requirements
  i. Replaceable parts:
     - Skull, to a skull with different mass and dimensions.
  ii. Adaptable parts: None

4. Skull-internal transfer

To allow for a realistic transfer of forces and movements from the skull to the brain, the following requirements must be met:

- Requirements for geometry and mechanics

  To allow for realistic transfer of forces and movements the CSF, bridging veins and eyes need to have realistic properties.

  i. Available information on geometry and mechanics
     - **CSF** properties:
       - CSF volume: 8 ml for neonates, 20 ml for 2-year-olds and 26 ml for adults [6].
       - CSF density vs brain density: 1.00059 ± 0.00020 g/ml and 1.0431 g/ml[7].
       - CSF viscosity: 0.7-1mPa*s (37 degrees Celsius) (Newtonian fluid) [8].
       - CSF pressure: is 3-4 mmHg in infants [6].
     - **Bridging veins** elongation properties:
       - Ultimate tensile stress and tensile strain: presented in Appendix A.7, Table 1 and Table 2 [2, 9].
       - Stress-strain relation: presented in Appendix A.7, Table 3 [2, 9].
       - Elastic modulus: presented in Appendix A.7, Table 4 [2, 9].
       - Relaxation behaviour: presented in Appendix A.7, Figure 1. The peak stresses become much larger when more stretching cycles have been performed. A recovery of 10 minutes is too short to recover the peak stresses. The peak stress was 3.677 ± 2.426 MPa and decreased to a steady state stress of 0.962 ± 1.058 MPa. After 30 cycles, the yield stretch became higher while the ultimate stretch did not vary significantly [2, 9].
     - **Eye** properties:
       - Peak tensile stresses at posterior side: maximum of around 0.62 kPa [10].
       - Peak compressive stresses at posterior side: maximum of around 0.85 kPa [10].
       - Intraocular pressure: presented in Appendix A.7, Table 5 [11].
       - Elastic modulus, Poisson's ratio and density presented in Appendix A.7, Table 6 [12].

  ii. Yet to be determined:

     If the brain and CSF densities, CSF viscosity, elastic modulus of eye tissue, Poisson's ratio of eye tissue and density of eye tissue vary over age. If the bridging veins elongation properties of 0-12 months old infants are similar to the elongation properties of 0-3 years old infants.

     (important due to the fact that the brain damage could be differing when the density and viscosity properties of CSF changes significantly, the properties of eye tissue are important as well due to the fact that when materials with realistic properties are used, the damaging of the real eye-tissue could be researched)

  iii. Assumptions:

     The brain and CSF densities, the elastic modulus of eye tissue, the Poisson's ratio of eye tissue and the density of eye tissue are similar for adults and infants.

     The bridging veins elongation properties are assumed to be similar for 0-12 months old infants and 0-3 years old infants.

  iv. Working requirements
     - Minimum:
       - The following properties of **CSF** are used in the model: volume for 2-year olds (20 ml), density of 1 g/ml for both CSF and brain, viscosity of water (0.6913mPa*s) and pressure of 3-4 mmHg.

- **Bridging veins** elongation properties:
  Elongations are represented by marking points on the inside of the skull and outside of the brain (movements relative to each other could be measured).
- The **eye** is represented by a material which does not have the same mechanical and material properties but only has a realistic intraocular pressure.

- Desired
  - The following properties of **CSF** are used in the model: volume for 2-year olds (20 ml), density of 1 g/ml and 1.0431 g/ml for CSF and brain respectively, viscosity of 0.7-1 mPa*s and pressure of 3-4 mmHg.
  - **Bridging veins** elongations are represented by a real connection between the skull and brain with similar ultimate stress and strain, yield stress and strain and elastic modulus.
  - The **eye** is represented by a material which does have realistic mechanical and material properties and intraocular pressure.
- Ideal
  - The following properties of **CSF** are used in the model: volume for neonates (8ml) (adjustable within 8 (neonates) and 26 ml (adults) to research its influence), density of 1 g/ml and 1.0431 g/ml for CSF and brain respectively, viscosity of 0.7-1 mPa*s and pressure of 3-4 mmHg (adjustable to research its influence).
  - Bridging veins **elongations** are represented by a real connection between the skull and brain with similar ultimate stress and strain, yield stress and strain, elastic modulus and relaxation properties.
  - The **eye** is represented by a material which does have the same mechanical and material properties. Next to that the intraocular pressure is adjustable within the range of the youngest to the oldest infants.

- Measurement requirements

  i. <u>What to measure</u> (variables, directions):
  Internal interactions and pressures:
  - Interaction of CSF and brain
    - Minimum, desired & ideal: measuring the CSF pressure differences during shaking.
  - Eye pressure
    - Minimum, desired & ideal: measuring the pressure differences during shaking inside the eye.
  - Movements/velocities/accelerations of brain and skull relative to each other
    - Minimum: measuring the brain and skull movements over time, to allow comparison between them.
    - Desired & ideal: measuring the brain and skull movements over time and presenting them together in diagrams to allow easy comparison.
  - Interaction of brain and skull
    - Minimum: measuring if the brain hits the skull during shaking.
    - Desired: measuring at which time point the brain hits the skull during shaking.
    - Ideal: measuring at which time point and with which force the brain hits the skull during shaking.
  - Strain and failure of bridging veins
    - Minimum: measuring if the bridging veins have been elongated during shaking.
    - Desired: measuring how much the bridging veins have been elongated during shaking.

- Ideal: measuring how much the bridging veins elongates over time and the amount of cycles of elongation over time during the shaking movements.
- Stress in bridging veins
  - Minimum & desired: measuring the stress inside the bridging veins.
  - Ideal: measuring the stress, peak stress and the cycles to failure over time inside the bridging veins.

ii. How to measure (accuracy, resolution, range):
TBD

Usability requirements

i. Replaceable parts:
- Material of fluids/internal anatomical structures: CSF, brain, bridging veins and eyes, to fluids/structures with other material properties

ii. Adaptable parts: None

5. Internal dynamics,

To allow for realistic internal dynamics, the following requirements must be met:

- Requirements for geometry and mechanics

  To allow for realistic internal dynamics the brain needs to have realistic properties.

  i. Available information on geometry and mechanics
     - Brain properties:
       - Shear storage, shear loss and complex moduli: presented in Appendix A.8, Table 1, Table 2 and Table 3 [1, 2, 13, 14].
       - Shear stiffness and damping ratio: presented in Appendix A.8, Table 4 and Table 5 [2, 15].
       - Elasticity score: presented in Appendix A.8, Table 6 [2, 16].
       - Relaxation behaviour: a decreasing shear modulus is the consequence of an increasing time after the application of load (at persons in age range 4-58 year). This is shown in Appendix A.8, Figure 1 and Figure 2 [1, 2].
     - Brain volume: presented in Appendix A.8, Table 7 [17].

  ii. Yet to be determined:

     If the shear storage and shear loss moduli are similar for 5- and 12-months old infants and 0-3 years old infants. If the complex shear modulus is similar for 0-3 years old infants and adults. If the brain stiffness and damping ratio is similar for infants of 0-3 years old infants and adolescents. If the elasticity score is similar for neonates and 0-3 years old infants. If the relaxation behaviour varies over age. What the brain volume is of 3 years old infants. (important due to the fact that the brains reaction onto shaking movements varies when shear moduli are varying significantly, the relaxation behaviour is also relevant due to the fact that the brains material could restore to its original shape and therefore may react differently onto shaking movements)

  iii. Assumptions:

     The shear storage and shear loss moduli are similar for infants of 5 and 12 months old and for infants of 0-3 years old.
     The complex shear modulus is similar for infants and adults.
     The brain stiffness and damping ratio of adolescents gives an indication of the stiffness and damping ratio of the brain of infants of 0-3 years old.
     The elasticity score of the brain of neonates is similar to the elasticity score of the brain of infants of 0-3 years old.
     Relaxation behaviour is similar for 4-58 year olds and 0-3 year olds.
     The brain volume of 2 years old infants summed up with the standard deviation gives an indication of the brain volume of a 3 year old infant.

  iv. Working requirements
     - Minimum: the brain is represented in the model by a material with similar elasticity. The volume of the total brain falls within the volume values (of the youngest till the oldest infants) of the total brain volume (TBV).
     - Desired: the brain is represented in the model by a material with similar shear moduli, stiffness moduli, damping ratios, elasticity scores and volumes for the various brain regions.
     - Ideal: the brain is represented in the model by a material with the same properties (including relaxation behaviour) and the same brain region volumes.

- Measurement requirements
  i. <u>What to measure</u> (variables, directions):
     - The movements, velocities and accelerations of the brain:
       - Minimum: measuring if the brain has moved, measuring peak velocity of the brain and measuring peak acceleration of the brain.
       - Desired & ideal: measuring the distance over which the brain has moved, measuring the brain velocity over time during the total amount of shaking movements and measuring the brain acceleration over time during the total amount of shaking movements. Appendix A.5., Table 1 and Table 2

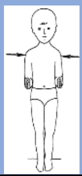
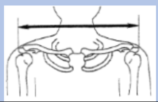
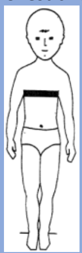
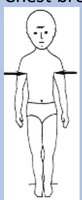
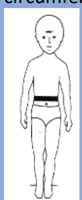
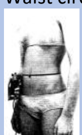
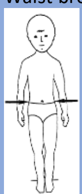
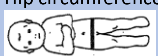
  ii. <u>How to measure</u> (accuracy, resolution, range):
     TBD

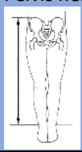
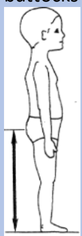
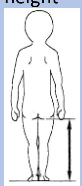
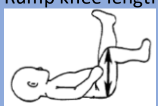
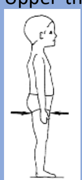
- Usability requirements
  i. <u>Replaceable parts:</u>
     - Material of brain, to material with other properties.

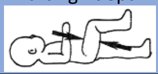
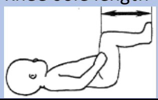
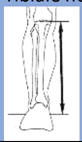
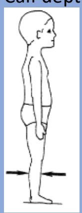
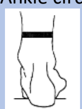
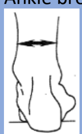
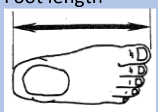
  ii. <u>Adaptable parts:</u> None

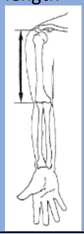
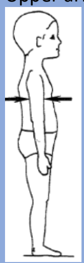
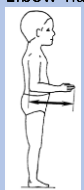
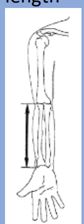
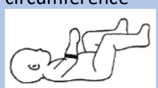
Appendix A.1.
Anthropomorphic data

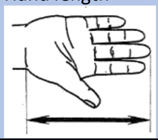
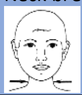
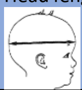
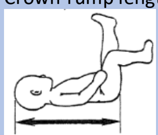
Table 1. Overview of the anthropomorphic data (mean and standarddeviation (SD)) of the torso, limbs, neck, head and combinations of them [18].

Body part		Age range (months)	0-2	3-5	6-8	9-11	12-15	16-19	20-23	24-42	24-42 males	24-42 females
Torso	Shoulder breadth 	Mean (cm)	16.7	18.7	20.1	21.1	21.3	21.7	22.4	24.4	24.7	24.1
		SD (cm)	1.6	1.4	1.2	1.3	1.3	1.3	1.3	1.5	1.5	1.5
	Biacromial breadth 	Mean (cm)								21.9	22.1	21.8
		SD (cm)								1.4	1.5	1.2
	Chest circumference 	Mean (cm)	37.1	40.4	43.4	45.1	46.3	46.8	47.7	50.7	51.3	49.9
		SD (cm)	2.5	2.4	1.8	2.3	2.3	2.2	2.2	2.7	2.6	2.6
	Chest breadth 	Mean (cm)	12.2	13.8	14.7	15.9	15.8	15.8	16.3	16.1	16.5	15.7
		SD (cm)	1.3	0.8	1.1	1.2	0.9	1.3	1.2	1.2	1.3	1.0
	Natural waist circumference 	Mean (cm)								47.0	47.8	46.1
		SD (cm)								3.1	3.0	2.9
	Waist circumference 	Mean (cm)	34.4	37.9	40.3	40.4	41.6	43.1	43.9	48.1	48.5	47.6
		SD (cm)	4.0	3.3	2.5	2.7	2.6	3.1	2.9	3.2	3.3	3.0
	Waist breadth 	Mean (cm)	11.6	12.6	13.5	14.1	14.3	14.6	14.9	16.1	16.3	15.9
		SD (cm)	1.4	1.3	1.0	1.1	1.1	1.2	0.8	1.0	1.1	0.9
	Hip circumference 	Mean (cm)	36.8	40.5	45.7	44.8	46.4	47.7	47.6	51.7	52.2	51.2
		SD (cm)	5.0	4.4	2.9	3.3	3.3	4.0	3.9	3.2	3.2	3.1

Body part		Age range (months)	0-2	3-5	6-8	9-11	12-15	16-19	20-23	24-42	24-42 males	24-42 females
	Hip breadth 	Mean (cm)	13.2	14.3	15.9	16.6	16.9	17.1	17.1	18.0	18.1	17.9
		SD (cm)	2.1	1.4	1.0	1.5	0.9	1.6	1.4	1.0	1.1	0.9
Limbs	Rump-sole length 	Mean (cm)	23.1	26.8	29.9	33.8	35.4	37.5	40.5			
		SD (cm)	1.9	2.4	2.3	3.7	2.1	2.9	3.4			
	Pelvis height 	Mean (cm)								51.4	51.3	51.6
		SD (cm)								3.6	3.7	3.6
	Hip height at buttocks 	Mean (cm)								40.4	41.3	39.4
		SD (cm)								2.9	2.8	2.7
	Trochanteric height 	Mean (cm)								42.6	42.5	42.8
		SD (cm)								3.3	3.4	3.3
	Gluteal furrow height 	Mean (cm)								37.5	37.3	37.7
		SD (cm)								2.9	2.8	3.1
	Rump knee length 	Mean (cm)	13.9	15.9	17.2	19.2	19.9	21.3	22.6			
		SD (cm)	1.5	1.7	1.5	1.7	1.6	1.7	2.4			
	Upper-thigh circumference 	Mean (cm)								29.1	28.9	29.2
		SD (cm)								2.5	2.5	2.6
	Upper-thigh depth 	Mean (cm)								8.5	8.5	8.4
		SD (cm)								0.9	0.9	1.0

Body part	Age range (months)	0-2	3-5	6-8	9-11	12-15	16-19	20-23	24-42	24-42 males	24-42 females
Mid-thigh circumference	Mean (cm)	16.9	20.7	21.2	23.2	23.4	24.4	24.7			
	SD (cm)	1.9	2.8	2.1	2.0	2.1	2.0	2.5			
Mid-thigh depth	Mean (cm)	5.2	5.9	6.2	6.9	7.0	7.0	7.2			
	SD (cm)	0.7	0.9	0.9	0.9	1.0	0.9	1.0			
Knee-sole length	Mean (cm)	14.9	16.5	17.9	19.8	20.8	21.6	23.0			
	SD (cm)	1.1	1.1	0.8	1.5	1.0	1.3	1.6			
Tibiale height	Mean (cm)								22.3	21.9	22.7
	SD (cm)								1.9	1.8	1.9
Calf circumference	Mean (cm)	13.7	15.6	16.9	18.1	18.1	18.4	19.0	20.6	20.7	20.4
	SD (cm)	2.1	1.5	1.3	1.2	1.3	1.2	1.3	1.5	1.4	1.5
Calf depth	Mean (cm)								6.2	6.4	6.0
	SD (cm)								0.5	0.4	0.5
Ankle circumference	Mean (cm)	10.2	11.6	12.3	12.9	13.2	13.3	13.6	14.8	14.9	14.8
	SD (cm)	1.5	1.0	0.9	1.0	1.0	1.1	0.9	1.0	0.9	1.1
Ankle breadth	Mean (cm)	3.0	3.4	3.6	3.8	3.9	3.9	4.0	4.1	4.2	4.1
	SD (cm)	0.4	0.3	0.3	0.4	0.4	0.3	0.3	0.4	0.3	0.4
Foot length	Mean (cm)	8.2	9.1	10.0	10.9	11.7	11.9	12.5	14.7	15.0	14.5
	SD (cm)	0.5	0.6	0.7	0.6	0.8	1.0	0.9	1.1	1.1	1.0
Foot breadth	Mean (cm)	3.6	4.0	4.2	4.7	4.9	5.0	5.2	6.1	6.3	5.9
	SD (cm)	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.5	0.4	0.4
Shoulder-elbow length	Mean (cm)	10.9	12.3	13.1	14.5	14.9	15.4	16.2	18.5	18.8	18.2
	SD (cm)	0.9	1.0	1.2	1.0	1.0	0.8	1.0	1.4	1.4	1.3

Body part		Age range (months) 0-2	3-5	6-8	9-11	12-15	16-19	20-23	24-42	24-42 males	24-42 females
Acromion-radiale length	Mean (cm)								16.7	16.9	16.5
	SD (cm)								1.0	1.0	1.0
Upper arm circumference	Mean (cm)	11.8	13.0	14.0	14.8	14.5	14.7	15.0	15.8	15.9	15.7
	SD (cm)	1.5	1.2	1.0	1.0	1.1	1.3	1.0	1.3	1.2	1.3
Upper arm depth	Mean (cm)								4.7	4.8	4.6
	SD (cm)								0.6	0.6	0.6
Elbow-hand length	Mean (cm)	14.9	16.6	18.0	19.6	19.9	20.7	21.5	24.4	24.8	24.0
	SD (cm)	1.0	1.3	1.1	1.3	0.8	1.5	1.1	1.6	1.7	1.5
Radiale-stylion length	Mean (cm)								13.5	13.7	13.2
	SD (cm)								1.1	1.2	1.0
Forearm circumference	Mean (cm)	11.8	13.1	14.0	14.3	14.5	14.5	14.8	15.7	15.8	15.5
	SD (cm)	1.1	1.1	0.8	1.0	0.8	1.1	0.8	1.0	1.1	1.0
Forearm breadth	Mean (cm)								4.7	4.8	4.5
	SD (cm)								0.4	0.5	0.4
Wrist circumference	Mean (cm)	9.1	10.2	10.5	10.8	10.9	10.7	10.9	11.3	11.4	11.2
	SD (cm)	0.9	0.9	0.6	0.8	0.9	1.0	0.8	0.8	0.8	0.9
Wrist breadth	Mean (cm)								2.9	3.0	2.9
	SD (cm)								0.3	0.3	0.3

	Body part \ Age range (months)		0-2	3-5	6-8	9-11	12-15	16-19	20-23	24-42	24-42 males	24-42 females
	Hand length 	Mean (cm)	6.8	7.4	8.0	8.9	9.2	9.3	9.5	10.5	10.7	10.3
		SD (cm)	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.7	0.8	0.6
	Hand Breadth 	Mean (cm)	3.7	4.1	4.2	4.5	4.6	4.6	4.7	5.1	5.2	5.0
		SD (cm)	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.3
Neck	Neck circumference 	Mean (cm)								23.8	24.2	23.4
		SD (cm)								1.2	1.1	1.1
	Neck breadth 	Mean (cm)								7.1	7.3	7.0
		SD (cm)								0.6	0.6	0.5
Head	Head circumference 	Mean (cm)	38.5	41.7	43.9	45.5	46.6	46.8	47.8	49.5	50.2	48.7
		SD (cm)	1.9	1.4	1.3	1.4	1.4	1.8	1.9	1.7	1.6	1.5
	Head breadth 	Mean (cm)	10.4	11.4	11.8	12.2	12.7	12.7	12.9	13.4	13.6	13.2
		SD (cm)	0.5	0.5	0.4	0.5	0.4	0.4	0.5	0.6	0.6	0.5
	Head length 	Mean (cm)	13.4	14.6	15.5	16.0	16.7	16.7	17.1	17.5	17.8	17.2
		SD (cm)	0.8	0.6	0.6	0.7	0.7	0.7	0.8	0.7	0.7	0.6
	Head height 	Mean (cm)								17.3	17.6	17.0
		SD (cm)								1.0	1.1	0.8
Total lengths and lengths of combinations of body parts	Crown-sole length 	Mean (cm)	56.3	63.1	68.5	73.0	76.5	79.2	82.6	93.4	94.5	92.1
		SD (cm)	3.9	3.6	2.6	3.3	3.2	3.4	4.0	5.0	5.0	4.7
	Crown-rump length 	Mean (cm)	39.1	42.3	45.7	47.6	49.0	49.8	51.5			
		SD (cm)	2.8	2.4	2.3	2.2	2.1	2.0	2.4			
	Suprasternale height 	Mean (cm)								72.4	72.7	72.0
		SD (cm)								4.1	4.2	4.0
		Mean (cm)								65.2	66.6	63.8

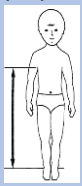
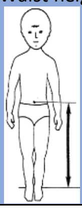
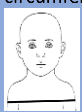
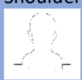
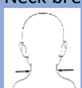
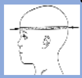
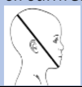
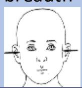
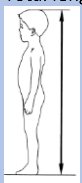
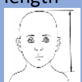
Body part		Age range (months)	0-2	3-5	6-8	9-11	12-15	16-19	20-23	24-42	24-42 males	24-42 females
	Chest height at axilla 	SD (cm)								3.7	3.4	3.5
	Waist height 	Mean (cm)								49.3	50.4	48.2
		SD (cm)								3.3	3.1	3.2

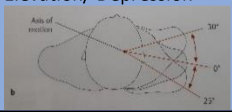
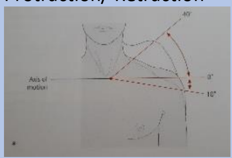
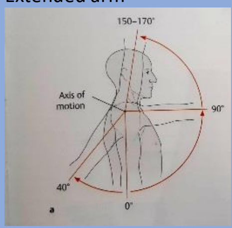
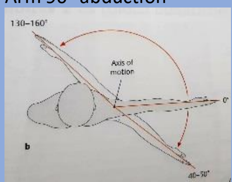
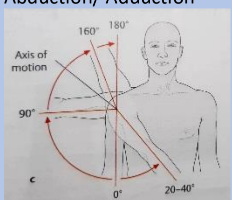
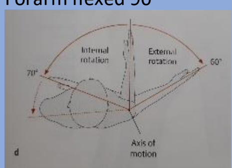
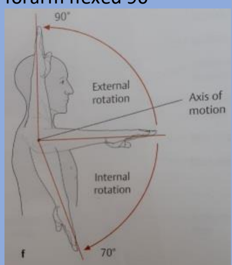
Table 2. Overview of the additional anthropomorphic data (mean and standard deviation (SD)) of the torso, limbs, neck, head and combinations of them [19].

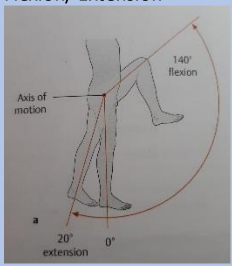
Body part		Age range (months)	0-3	4-6	7-9	10-12	13-18	19-24	25-30	31-36	37-42
Torso	Shoulder circumference 	Mean (cm)	45.4	48.9	53.7	54.9	55.9	59.2	59.3	62.0	64.5
		SD (cm)	4.0	3.3	3.7	3.1	3.2	3.5	4.0	3.2	3.0
	Shoulder breadth 	Mean (cm)	17.6	20.0	20.3	21.2	22.5	23.2	23.9	24.4	25.5
		SD (cm)	1.3	1.5	1.6	1.4	1.3	0.9	1.5	1.6	1.2
	Torso depth 	Mean (cm)	9.5	10.6	10.8	11.1	11.7	11.3	12.3	11.9	12.3
		SD (cm)	0.8	0.8	0.9	0.9	0.9	0.8	0.7	0.7	0.7
Limbs	Shoulder depth 	Mean (cm)	5.0	5.7	5.9	5.9	6.2	6.2	6.6	6.3	6.6
		SD (cm)	0.7	0.6	0.7	0.5	0.6	0.5	0.7	0.6	0.6
Neck	Neck circumference 	Mean (cm)	21.4	21.4	21.8	21.9	21.9	22.3	22.8	22.9	23.2
		SD (cm)	2.1	1.1	1.9	1.3	1.2	1.2	1.5	1.2	1.1
	Neck breadth 	Mean (cm)	5.7	6.1	6.3	6.8	6.7	6.9	7.1	7.1	7.4
		SD (cm)	0.5	0.6	0.4	0.6	0.6	0.5	0.5	0.5	0.5
	Neck depth 	Mean (cm)	6.1	6.2	6.3	6.6	6.4	6.6	6.7	6.7	6.9
		SD (cm)	0.7	0.7	0.5	0.5	0.4	0.6	0.5	0.4	0.4
Head	Head height 	Mean (cm)	13.6	14.5	15.1	15.8	16.3	16.8	17.3	17.5	17.9
		SD (cm)	1.0	0.8	0.9	0.9	0.8	0.6	0.9	0.9	1.1
	Head circumference	Mean (cm)	39.5	43.5	44.8	46.1	47.8	48.5	49.9	49.7	50.0
		SD (cm)	1.4	1.6	1.3	1.8	1.5	1.4	1.7	1.5	1.2

	Body part	Age range (months)	0-3	4-6	7-9	10-12	13-18	19-24	25-30	31-36	37-42
											
	Head breadth 	Mean (cm)	10.4	11.5	12.1	12.3	12.7	13.1	13.1	13.3	13.4
		SD (cm)	0.5	0.6	0.4	0.5	0.4	0.6	0.4	0.4	0.5
	Head length 	Mean (cm)	13.9	15.4	15.8	16.3	16.8	17.2	17.7	17.7	17.8
		SD (cm)	0.6	0.6	0.5	0.8	0.6	0.6	0.7	0.6	0.6
	Chin to back circumference 	Mean (cm)	43.3	47.5	49.0	50.6	52.0	52.9	54.4	54.4	55.1
		SD (cm)	1.5	1.6	1.7	2.0	1.7	1.6	1.8	1.6	1.7
	Chin to back distance 	Mean (cm)	16.1	17.7	18.0	18.9	19.3	19.8	20.3	20.5	20.9
		SD (cm)	0.6	0.7	0.7	0.7	0.7	0.6	0.8	0.6	0.7
	Maximum face breadth 	Mean (cm)	8.8	9.5	9.5	9.8	9.9	10.0	10.2	10.4	10.4
		SD (cm)	0.5	0.5	0.7	0.6	0.6	0.5	0.5	0.5	0.4
lengths of combinations of body parts	Total length 	Mean (cm)	58.3	66.0	69.6	74.8	79.0	85.0	89.2	93.0	97.8
		SD (cm)	3.4	3.2	2.9	3.2	4.1	3.1	3.8	4.0	3.9
	Crown-rump length 	Mean (cm)	40.0	43.2	46.0	48.3	49.3	51.2	52.0	53.8	55.1
		SD (cm)	2.6	2.1	1.7	2.2	2.7	2.1	2.6	2.6	3.0
	Shoulder to head length 	Mean (cm)	14.9	15.3	16.4	17.7	17.4	18.7	18.6	19.7	19.4
		SD (cm)	1.1	1.1	1.1	1.1	1.1	1.7	1.4	1.6	1.4
	Shoulder circumference point to head length 	Mean (cm)	17.5	18.0	19.7	20.8	21.0	22.5	22.6	24.2	24.0
		SD (cm)	1.7	1.6	1.2	1.3	1.3	1.8	2.0	1.4	1.5

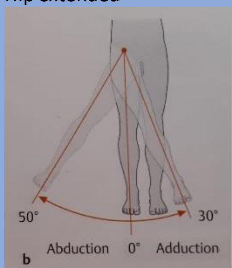
Appendix A.2.
Degrees of freedom, range of motion and joint stiffness

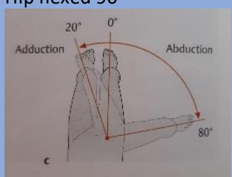
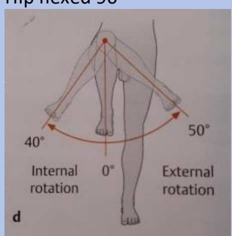
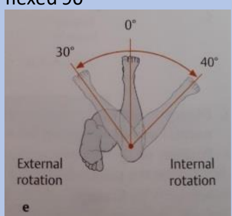
Table 1. Overview of the available information according to the degrees of freedom [20, 21], range of motion [20, 22-27] and passive stiffness [28-43] of the human joints, neck and thoracic & lumbar spine for several age categories.

Joint (#DOF) [20, 21]	Schematic drawing of the joint movements [20]	Movement range of motion (°)			Passive joint stiffness (Nm/°)
		Adults [20]	Youngsters (18 mos. – 19 yrs.) [23, 24]	Infants (0 - 2 yrs.) [22, 23]	
Shoulder (5)	Elevation/ Depression 	Elevation: 40° Depression: 10°	-	-	-
	Protraction/ Retraction 	Protraction: 30° Retraction: 25°	-	-	-
	Flexion/ Extension – Extended arm 	Flexion: 150 °-170 ° Extension: 40 °	Flexion: 168° ± 4° Extension: 68° ± 8°	Flexion: 172°-180° Extension: 79°-89°	-
	Flexion/ Extension – Arm 90° abduction 	Flexion: 130°-160° Extension: 40°-50°	-	-	Passive stiffness, 29 ± 7 yrs. [43]: < 0.4 ± 0.3 Nm/rad → < 0.007 ± 0.005 Nm/°
	Abduction/ Adduction 	Abduction: 180° Adduction: 20°-40°	Abduction: 185°±4° Adduction: -	Abduction: 177°-187° Adduction: -	Passive stiffness, 29 ± 7 yrs. [43]: 1.7 ± 0.7 Nm/rad → 0.039 ± 0.012 Nm/°
	Internal rotation/ External rotation – Forarm flexed 90° 	Internal rotation: 70° External rotation: 60°	-	-	-
	Internal rotation/ External rotation – Arm abduction 90° and forarm flexed 90° 	Internal rotation: 70° External rotation: 90°	Internal rotation: 71° ± 5° External rotation: 108° ± 7°	Internal rotation: 72°-90° External rotation: 123° More specified external rotation: - 0 wks.: 134° - 2-4 wks.: 126° - 4-8 mos.: 120° - 8-12 mos.: 124° - 1 yr.: 116° - 2 yrs.: 118°	Passive stiffness, 29 ± 7 yrs. [43]: 1.4 ± 0.9 Nm/rad → 0.024 ± 0.016 Nm/°

<table>
<tr><th rowspan="2">Joint (#DOF) [20, 21]</th><th colspan="2" rowspan="2">Schematic drawing of the joint movements [20]</th><th colspan="3">Movement range of motion (°)</th><th rowspan="2">Passive joint stiffness (Nm/°)</th></tr>
<tr><th>Adults [20]</th><th>Youngsters (18 mos. – 19 yrs.) [23, 24]</th><th>Infants (0 - 2 yrs.) [22, 23]</th></tr>
<tr><td rowspan="5">Hip (3)</td><td colspan="2">Flexion/ Extension

</td><td>Flexion: 140°
Extension: 20°</td><td>Flexion: 123° ± 6°
Extension: 7° ± 7°</td><td>Flexion: 136°
Extension: -1°

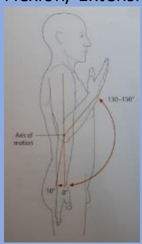
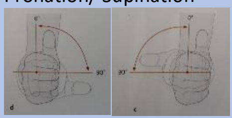
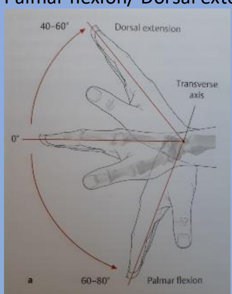
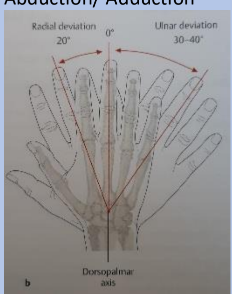
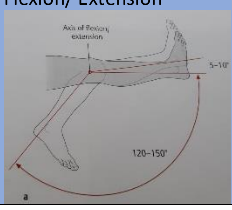
More specified Flexion:
Neonates: 120°
4 wks.: 138°
4-8 mos.: 136°
8-12 mos.: 138°
1 yr.: 141°
2 yrs.: 143°

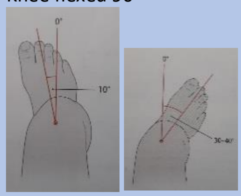
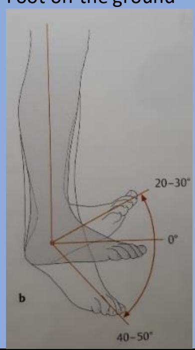
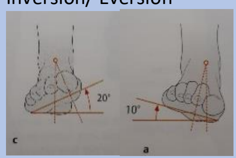
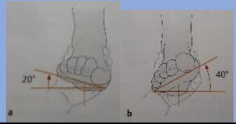
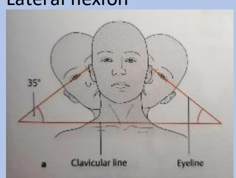
More specified Extension:
Neonates: -25°
4 wks.: -12°
4-8 mos.: -4°
8-12 mos.: 3°
1 yr.: 15°
2 yrs.: 21°</td><td>-</td></tr>
<tr><td rowspan="2">Abduction/ Adduction</td><td>Hip extended

</td><td>Abduction: 50°
Adduction: 30°</td><td>Abduction: 52° ± 9°
Adduction: 28° ± 4°</td><td>Abduction: 57°
Adduction 17° ± 4°

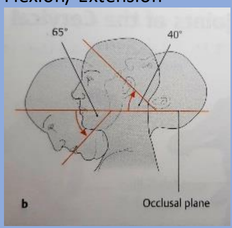
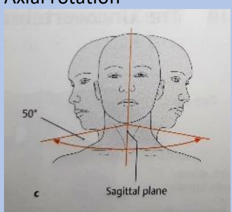
More specified Abduction:
Neonates: 48°
4 wks.: 51°
4-8 mos.: 55°
8-12 mos.: 60°
1 yr.: 66°
2 yrs.: 63°</td><td rowspan="2">-</td></tr>
<tr><td>Hip flexed 90°

</td><td>Abduction: 80°
Adduction: 20°</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Internal rotation/ External rotation</td><td>Hip flexed 90°

</td><td>Internal rotation: 40°
External rotation: 50°</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hip extended and leg flexed 90°

</td><td>Internal rotation: 40°
External rotation: 30°</td><td>Internal rotation 50° ± 6°
External rotation: 51° ± 6°</td><td>Internal rotation: 38°
External rotation: 70°

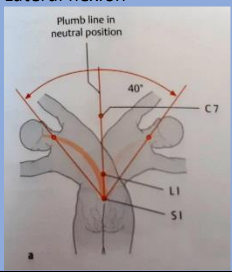
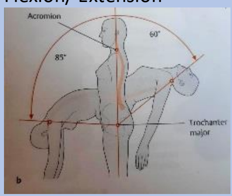
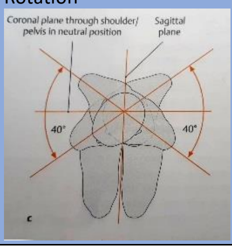
More specified Internal rotation:
Neonates: 21°
4 wks.: 24°
4-8 mos.: 39°
8-12 mos.: 38°
1 yr.: 49°
2 yrs.: 59°

More specified External rotation:</td><td>Stiffness, 24.8 ± 4.2 yrs. [28]
Passive:
Mean passive stiffness: 5.61 ± 5.35 Nm/rad → 0.098 ± 0.093 Nm/°</td></tr>
</table>

Joint (#DOF) [20, 21]	Schematic drawing of the joint movements [20]	Movement range of motion (°)			Passive joint stiffness (Nm/°)
		Adults [20]	Youngsters (18 mos. – 19 yrs.) [23, 24]	Infants (0 - 2 yrs.) [22, 23]	
				Neonates: 77° 4 wks.: 66° 4-8 mos.: 66° 8-12 mos.: 79° 1 yr.: 74° 2 yrs.: 58°	
Elbow (2)	Flexion/ Extension 	Flexion: 130°-150° Extension: 10°	Flexion: 145° ± 5° Extension: 1° ± 4°	Flexion: 148°-158° Extension -2° More specified extension: 0 wks.: -14° 2-4 wks.: -6° 4-8 mos.: 0° 8-12 mos.: 1° 1 yr.: 3° 2 yrs.: 5°	Passive stiffness, females: 23.4 ± 3.5 yrs., males: 20.9 ± 1.6 yrs. [29] 0.013± 0.005 Nm/°
	Pronation/ Supination 	Pronation: 90° Supination: 90°	pronation: 77° ± 5° Supination: 83° ± 3°	Pronation: 90°-96° Supination: 81°-93°	Passive stiffness, 24-42 yrs. [30] Pronation Males: 0.285 ± 0.120 (Nm/rad) → 0.005 ± 0.002 Nm/° Females: 0.135 ± 0.107 Nm/rad → 0.002 ± 0.002 Nm/° Supination Males: 0.217 ± 0.093 Nm/rad → 0.004 ± 0.002 Nm/° Females: 0.114 ± 0.083 Nm/rad → 0.002 ± 0.001 Nm/°
Wrist (2)	Palmar flexion/ Dorsal extension 	Palmar flexion: 60°-80° Dorsal extension: 40°-60°	Flexion: 78° ± 6° Extension: 76° ± 6°	Flexion: 88°-96° Extension: 82°-89°	Passive stiffness, 24-42 yrs. [30] Flexion Males: 0.605 ± 0.131 Nm/rad → 0.011 ± 0.002 Nm/° Females: 0.429 ± 0.192 Nm/rad → 0.007 ± 0.003 Nm/° Extension Males: 1.146 ± 0.327 Nm/rad → 0.020 ± 0.006 Nm/° Females: 0.717 ± 0.323 Nm/rad → 0.013 ± 0.006 Nm/°
	Abduction/ Adduction 	Abduction (Radial deviation): 20° Adduction (Ulnar deviation): 30°-40°	Abduction: 22° ± 4° Adduction: 37° ± 4°	-	Passive stiffness, 24-42 yrs. [30] Abduction Males: 1.927 ± 0.521 Nm/rad → 0.034 ± 0.009 Nm/° Females: 1.205 ± 0.314 Nm/rad → 0.021 ± 0.005 Nm/° Adduction: Males: 1.328 ± 0.468 Nm/rad → 0.023 ± 0.008 Nm/° Females: 1.035 ± 0.315 Nm/rad → 0.018 ± 0.005 Nm/°
Knee (2)	Flexion/ Extension 	Flexion: 120°-150° Extension: 5°-10°	Flexion: 144° ± 5° Extension: 2° ± 3°	Flexion: 148°-159° Extension: 4°	Passive stiffness, 29 ± 7 yrs. [31] 28.7 ± 15.4 Nm/rad → 0.501 ± 0.269 Nm/°

Joint (#DOF) [20, 21]	Schematic drawing of the joint movements [20]		Movement range of motion (°)			Passive joint stiffness (Nm/°)
			Adults [20]	Youngsters (18 mos. – 19 yrs.) [23, 24]	Infants (0 - 2 yrs.) [22, 23]	
	Internal rotation/ External rotation	Knee flexed 90° 	Internal rotation: 10° External rotation: 30°-40°	External rotation [25]: 3-4 yrs.: 5° 5-7 yrs.: 10° 9 yrs.: 7° 11 yrs.: 10° 15-19 yrs.: 7°	External rotation [25]: 0 wks.: -14° 1 yr.: -5° 2 yrs.: 4°	Approximation of passive stiffness (read out from figure), males 29.3 ± 4.47 yrs., females 29.6 ± 8.68 yrs. [32] 0°: 13 Nm/rad → 0.227 Nm/° (males), 10 Nm/rad → 0.175 Nm/° (females) Internal rotation Males for 5°, 10° and 15° respectively: 15 Nm/rad → 0.262 Nm/°, 20 Nm/rad → 0.349 Nm/°, 39 Nm/rad → 0.681 Nm/° Females for 5°, 10° and 15° respectively: 14 Nm/rad → 0.244 Nm/°, 19 Nm/rad → 0.332 Nm/°, 38 Nm/rad → 0.663 Nm/° External rotation Males for 5°, 10° and 15° respectively: 16 Nm/rad → 0.279 Nm/°, 19 Nm/rad → 0.332 Nm/°, 37 Nm/rad → 0.646 Nm/° Females for 5°, 10° and 15° respectively: 10 Nm/rad → 0.175 Nm/°, 12 Nm/rad → 0.209 Nm/°, 19 Nm/rad → 0.332 Nm/°
Ankle (3)	Plantar flexion/ Dorsal extension	Foot off the ground 	Plantar flexion: 20°-30° Dorsal extension: 40°-50°	Plantar flexion 58° ± 6° Dorsal extension 13° ± 5°	Plantar flexion: 56° Dorsal extension: 48°	Passive stiffness, 32 ± 5 yrs. [33] Plantar flexion 18.14 ± 7.37 Nm/rad → 0.321 ± 0.129 Nm/° Dorsal extension 30.13 ± 18.13 Nm/rad → 0.526 ± 0.316 Nm/°
	Inversion/ Eversion 		Inversion: 20° Eversion: 10°	Inversion: 38° ± 5° Eversion: 22° ± 5°	Neonates [23, 26]: Inversion : 99° ± 6° Eversion 82° ± 9°	Passive stiffness, 32 ± 5 yrs. [33] Inversion: 19.7 ± 3.26 Nm/rad → 0.344 ± 0.057 Nm/° Eversion: 28.19 ± 7.46 Nm/rad → 0.492 ± 0.130 Nm/°
	Pronation/ supination 		Pronation: 20° Supination: 40°	-	-	-
Neck/ cervical spine (6)	Lateral flexion 		Lateral flexion: 35 °		Lateral flexion [27]: 2 mos.: 68.1° 4 mos.: 69.5° 6 mos.: 69.2° 10 mos.: 70°	Passive stiffness (Nm/°), males 19.5 ± 1.4 yrs., females 20.0 ± 1.6 yrs. [34] Lateral bending to right: Males 0.05, 0.09, 0.16, 0.29 for combinations of angles and bending moments: 10 and 0.8, 20 and 1.5, 30 and 2.7, 40 and 4.9. Females 0.03, 0.04, 0.08, 0.19 for combinations of angles and bending moments: 10 and 0.5, 20 and 0.8, 30 and 1.4, 40 and 2.4 Lateral bending to left: Males 0.05, 0.09, 0.17, 0.31

Joint (#DOF) [20, 21]	Schematic drawing of the joint movements [20]	Movement range of motion (°)			Passive joint stiffness (Nm/°)
		Adults [20]	Youngsters (18 mos. – 19 yrs.) [23, 24]	Infants (0 - 2 yrs.) [22, 23]	
					for combinations of angles and bending moments: 10 and 0.9, 20 and 1.6, 30 and 2.9, 40 and 5.2. Females 0.03, 0.05, 0.10, 0.20 for combinations of angles and bending moments: 10 and 003, 20 and 0.05, 30 and 0.10, 40 and 0.20. Passive cervical disc stiffness (Nm/°) (exceeding 1 Nm), cadaveric segments [38, 39]: 0.330 Nm/° More specific values shown in Figure 1.
	Flexion/ Extension  	Flexion: 65 ° Extension 40 °			Neck stiffness used in other dolls: 17 Nm/rad= 0.30 Nm/° [36] Passive stiffness (Nm/°), males 19.5 ± 1.4 yrs., females 20.0 ± 1.6 yrs. [34] Flexion: Males 0.05, 0.08, 0.12, 0.17, 0.26 for combinations of angles and bending movements: 10 and 1.2, 20 and 1.9, 30 and 2.8, 40 and 4.3, 50 and 6.4) Females 0.04, 0.06, 0.08, 0.13, 0.19 for combinations of angles and bending movements: 10 and 1.0, 20 and 1.4, 30 and 2.1, 40 and 3.2, 50 and 4.8 Extension: Males 0.03, 0.05, 0.07, 0.12, 0.19, 0.30 for combinations of angles and bending movements: 10 and 0.6, 20 and 1.0, 30 and 1.6, 40 and 2.5, 50 and 4.0, 60 and 6.4 Females 0.01, 0.02, 0.04, 0.08, 0.14, 0.26 for combinations of angles and bending movements: 10 and 0.2, 20 and 0.4, 30 and 0.7, 40 and 1.2, 50 and 2.3, 60 and 4.3.
	Axial rotation  	Rotation: 50 °		Rotation [27]: 2 mos.: 105.2° 4 mos.: 111.8° 6 mos.: 112.4° 10 mos.: 111.7°	Passive stiffness, 48 ± 14 yrs. [37] Rotation to the right 0.089 ± 0.035 Nm/° Rotation to the left 0.084 ± 0.031 Nm/° Passive cervical disc stiffness (Nm/°) (exceeding 1 Nm), cadaveric segments [38, 39]: 0.420 Nm/° More specific values shown in Figure 2
	Anterior/ Posterior translation	-	-	-	Passive cervical disc stiffness (N/mm), cadaveric segments [38, 39]: Anterior translation: 62 N/mm Posterior translation: 50 N/mm
	Lateral translation				Passive cervical disc stiffness (N/mm), cadaveric segments [38, 39]: 73 N/mm

Joint (#DOF) [20, 21]	Schematic drawing of the joint movements [20]	Movement range of motion (°)			Passive joint stiffness (Nm/°)
		Adults [20]	Youngsters (18 mos. – 19 yrs.) [23, 24]	Infants (0 - 2 yrs.) [22, 23]	
	Vertical tensional/ Vertical compressional translation				Passive cervical disc stiffness (N/mm), cadaveric segments: Vertical tensional translation: 68 N/mm [38, 40] Vertical compressional translation: 822-2931 [38, 41, 42]
Thoracic and lumbar spine (3)	Lateral flexion 	Thoracic: 20 ° Lumbar: 20 ° Total (incl. cervical spine): 75 °	-	-	Passive stiffness (Nm/°) lumbar spine, males 21.1 ± 1.2 yrs., females 20.8 ± 1.8 yrs. [35] Lateral flexion: 0.32 (2°), 0.40 (4°), 0.49 (6°), 0.61 (8°), 0.75 (10°), 0.93 (12°), 1.14 (14°), 1.41 (16°), 1.75 (18°), 2.16 (20°)
	Flexion/ Extension 	Thoracic Flexion: 35° Thoracic Extension: 25° Lumbar Flexion: 50° Lumbar Extension: 35° Total Flexion: 150° Total Extension: 100°	-	-	Passive stiffness (Nm/°) lumbar spine, males 21.1 ± 1.2 yrs., females 20.8 ± 1.8 yrs. [35] Flexion: 0.29 (2°), 0.36 (4°), 0.45 (6°), 0.56 (8°), 0.69 (10°), 0.86 (12°), 1.08 (14°), 1.34 (16°) Extension 0.17 (2°), 0.20 (4°), 0.23 (6°), 0.28 (8°), 0.32 (10°), 0.38 (12°), 0.45 (14°), 0.53 (16°), 0.62 (18°), 0.73 (20°), 0.86 (22°)
	Rotation 	Thoracic rotation: 35 ° Lumbar rotation: 5 ° Total rotation: 90 °	-	-	Passive stiffness (Nm/°) lumbar spine, males 21.1 ± 1.2 yrs., females 20.8 ± 1.8 yrs. [35] Rotation: 0.13 (2°), 0.15 (4°), 0.17 (6°), 0.20 (8°), 0.23 (10°), 0.26 (12°), 0.31 (14°), 0.36 (16°), 0.41 (18°), 0.48 (20°), 0.56 (22°), 0.64 (24°)

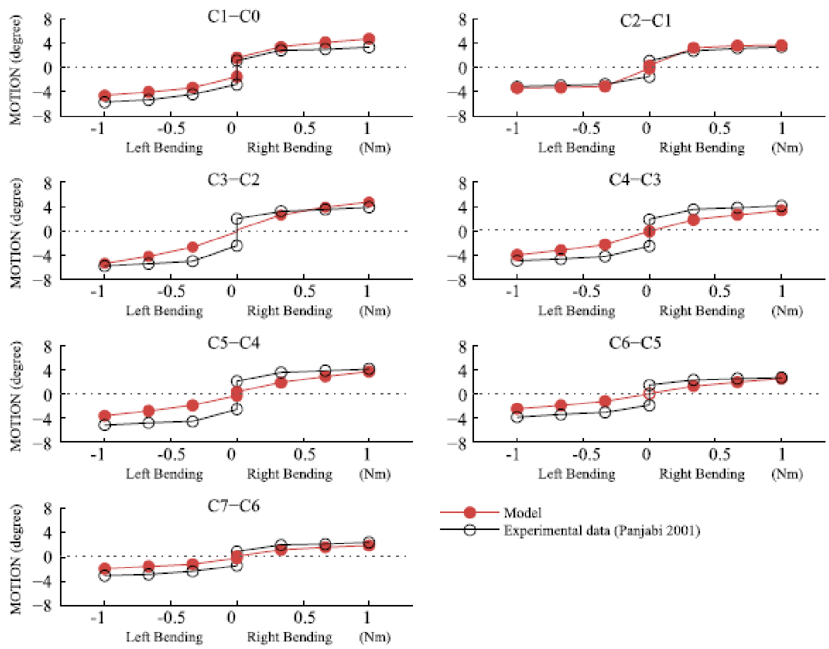


Figure 1. Passive stiffness lateral bending of cervical spine [38, 44].

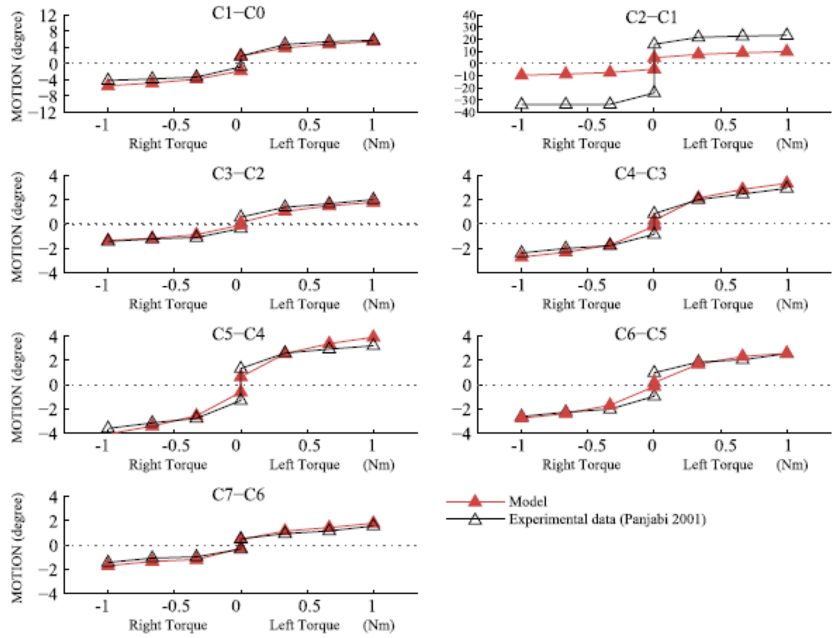


Figure 2. Passive stiffness axial rotation of cervical spine [41, 46].

Appendix A.3.
Working requirements DOF, ROM and passive stiffness

Table 1. Overview of the working requirements of the DOF and ROM of human joints, neck and thoracic & lumbar spine. The ROM's are based on the combination of ROM's of infants in the age range 0 to 2 years old (no underlining) [22, 23] and ROM's of humans in the age range of 18 months to 19 years old (_ _) [23, 24]. If no data was available, in those age categories, the data of adults (__) [20] was used to infer the ROM's.

Joint	Minimum DOF	Desired DOF and ROM	Ideal DOF and ROM (°)
Shoulder	0	3 - **Flexion/ Extension** ○ 0°-180°/ 0°-89° (extended arm) ○ 0°-160°/ 0°-50° (abducted arm) - **Abduction/ Adduction** ○ 0°-189°/ 0°-40° - **Internal rotation/ External rotation** ○ 0°-70°/ 0°-60° (flexed forearm) ○ 0°-90°/ 0°-134° (abducted arm and flexed forearm)	5 - **Elevation/ Depression** ○ 0°-40°/ 0°-10° - **Protraction/ Retraction** ○ 0°-30°/ 0°-25° - **Flexion/ Extension** ○ 0°-180°/ 0°-89° (extended arm) ○ 0°-160°/ 0°-50° (abducted arm) - **Abduction/ Adduction** ○ 0°-189°/ 0°-40° - **Internal rotation/ External rotation** ○ 0°-70°/ 0°-60° (flexed forearm) ○ 0°-90°/ 0°-134° (abducted arm and flexed forearm)
Hip	0	3 - **Flexion/ Extension** ○ 0°-143°/ -25°-21° - **Abduction/ Adduction** ○ 0°-63°/ 0°-32° (extended hip) ○ 0°-80°/ 0-20° (flexed hip) - **Internal rotation/ External rotation** ○ 0°-40°/ 0°-50° (flexed hip) ○ 0°-59°/ 0-79° (flexed leg)	3 - **Flexion/ Extension** ○ 0°-143°/ -25°-21° - **Abduction/ Adduction** ○ 0°-63°/ 0°-32° (extended hip) ○ 0°-80°/ 0-20° (flexed hip) - **Internal rotation/ External rotation** ○ 0°-40°/ 0°-50° (flexed hip) ○ 0°-59°/ 0-79° (flexed leg)
Elbow	0	1 - **Flexion/ Extension** ○ 0°-158°/ -14°-5°	2 - **Flexion/ Extension** ○ 0°-158°/ -14°-5° - **Pronation/ Supination** ○ 0°-96°/ 0°-93°
Wrist	0	1 - **Palmar flexion/ Dorsal extension** ○ 0°-96°/ 0°-89°	2 - **Palmar flexion/ Dorsal extension** ○ 0°-96°/ 0°-89° - **Abduction/ Adduction** ○ 0°-26°/ 0°-41°
Knee	0	1 - **Flexion/ Extension** ○ 0°-159°/ -1°-5°	2 - **Flexion/ Extension** ○ 0°-159°/ -1°-5° - **Internal rotation/ External rotation** ○ 0°-10° [20]/ -14°- 4° [25]
Ankle	0	1 - **Plantar flexion/ Dorsal extension** ○ 0°-64°/ 0°-48°	3 - **Plantar flexion/ Dorsal extension** ○ 0°-64°/ 0°-48° - **Inversion/ Eversion** ○ 0°-105° [23, 26]/ 0°-91° [23, 26] - **Pronation/ Supination** ○ 0°-20°/ 0°-40°

Joint	Minimum DOF	Desired DOF and ROM	Ideal DOF and ROM (°)
Neck (cervical spine)	0-1 - **Flexion/ Extension** ○ 0°-65°/ 0°-40°	3 - **Lateral flexion** ○ 0°-70° [27] - **Flexion/ Extension** ○ 0°-65°/ 0°-40° - **Axial rotation** ○ 0°-112.4° [27]	6 - **Lateral flexion** ○ 0°-70° [27] - **Flexion/ Extension** ○ 0°-65°/ 0°-40° - **Axial rotation** ○ 0°-112.4° [27] - **Anterior/ Posterior translation** ○ NA - **Lateral translation** ○ NA - **Vertical tensional/ Vertical compressional translation** ○ NA
Thoracic and Lumbar spine	0	1 - **Flexion/ Extension** ○ 0°-35° (thoracic), 0°-50° (lumbar), 0°-150° (total)/ 0°-25° (thoracic), 0°-35° (lumbar), 0°-100° (total)	3 - **Lateral flexion** ○ 0°-20° (thoracic), 0°-20° (lumbar), 0°-75° (total) - **Flexion/ Extension** ○ 0°-35° (thoracic), 0°-50° (lumbar), 0°-150° (total)/ 0°-25° (thoracic), 0°-35° (lumbar), 0°-100° (total) - **Rotation** ○ 0°-35° (thoracic), 0°-5° (lumbar), 0°-90° (total)

Table 2. Overview of the working requirements of the passive stiffness of the human joints, neck and thoracic & lumbar spine. No infant-data has been found for the passive stiffness, therefore these values are based on stiffness data retrieved from adults [28-43].

Joint	Minimum passive stiffness	Desired DOF and passive stiffness	Ideal passive stiffness (Nm/°)
Shoulder	Stiff	- **Flexion/ Extension** ○ NA (extended arm) ○ < 0.007 ± 0.005 Nm/° [43] (abducted arm) - **Abduction/ Adduction** ○ 0.039 ± 0.012 Nm/° [43] - **Internal rotation/ External rotation** ○ 0.024 ± 0.016 Nm/° [43]	5 - **Elevation/ Depression** ○ NA - **Protraction/ Retraction** ○ NA - **Flexion/ Extension** ○ NA (extended arm) ○ < 0.007 ± 0.005 Nm/° [43] (abducted arm) - **Abduction/ Adduction** ○ 0.039 ± 0.012 Nm/° [43] - **Internal rotation/ External rotation** ○ 0.024 ± 0.016 Nm/° [43]
Hip	Stiff	- **Flexion/ Extension** ○ NA - **Abduction/ Adduction** ○ NA - **Internal rotation/ External rotation** ○ 0.098 ± 0.093 Nm/° [28]	- **Flexion/ Extension** ○ NA - **Abduction/ Adduction** ○ NA - **Internal rotation/ External rotation** ○ 0.098 ± 0.093 Nm/° [28]
Elbow	Stiff	- **Flexion/ Extension** ○ 0.013 ± 0.005 N/° [29]	- **Flexion/ Extension** ○ 0.013 ± 0.005 N/° [29] - **Pronation/ Supination** ○ 0.005 ± 0.002 Nm/° (males, pronation) 0.002 ± 0.002 Nm/° (females, pronation) ○ 0.004 ± 0.002 Nm/° (males, supination) 0.002 ± 0.001 Nm/° (females, supination) [30]
Wrist	Stiff	- **Palmar flexion/ Dorsal extension** ○ 0.011 ± 0.002 Nm/° (males, flexion) 0.007 ± 0.003 Nm/° (females, flexion) ○ 0.020 ± 0.006 Nm/° (males, extension) 0.013 ± 0.006 Nm/° (females, extension) [30]	- **Palmar flexion/ Dorsal extension** ○ 0.011 ± 0.002 Nm/° (males, flexion) 0.007 ± 0.003 Nm/° (females, flexion) ○ 0.020 ± 0.006 Nm/° (males, extension) 0.013 ± 0.006 Nm/° (females, extension) [30] - **Abduction/ Adduction** ○ 0.034 ± 0.009 Nm/° (males, abduction) 0.021 ± 0.005 Nm/° (females, abduction) ○ 0.023 ± 0.008 Nm/° (males, adduction) 0.018 ± 0.005 Nm/° (females, adduction) [30]

Joint	Minimum passive stiffness	Desired DOF and passive stiffness	Ideal passive stiffness (Nm/°)
Knee	Stiff	- **Flexion/ Extension** ○ 0.501 ± 0.269 Nm/° [31]	- **Flexion/ Extension** ○ 0.501 ± 0.269 Nm/° [31] - **Internal rotation/ External rotation** ○ 0.227 Nm/° - 0.681 Nm/° (males, internal rotation) 0.175 Nm/° - 0.663 Nm/° (females, internal rotation) ○ 0.227 Nm/° - 0.646 Nm/° (males, external rotation) 0.175 Nm/° - 0.332 Nm/° (females, external rotation) [32]
Ankle	Stiff	- **Plantar flexion/ Dorsal extension** ○ 0.321 ± 0.129 Nm/° (plantar flexion) ○ 0.526 ± 0.316 Nm/° (dorsal extension) [33]	- **Plantar flexion/ Dorsal extension** ○ 0.321 ± 0.129 Nm/° (plantar flexion) ○ 0.526 ± 0.316 Nm/° (dorsal extension) [33] - **Inversion/ Eversion** ○ 0.344 ± 0.057 Nm/° (inversion) ○ 0.492 ± 0.130 Nm/° (eversion) [33] - **Pronation/ Supination** ○ NA
Neck (cervical spine)	- **Flexion/ Extension** ○ 0.05 Nm/° – 0.26 Nm/° (males, flexion) **0.04** Nm/° - 0.19 Nm/° (females, flexion) ○ **0.03** Nm/° - 0.30 Nm/° (males, extension) **0.01** Nm/° - 0.26 Nm/° (females, extension) [34]	- **Lateral flexion** ○ 0.05 Nm/° – 0.29 Nm/° (males, to the right) **0.03** Nm/° - 0.19 Nm/° (females, to the right) ○ **0.05** Nm/° - 0.31 Nm/° (males, to the left) **0.03** Nm/° - 0.20 Nm/° (females, to the left) [34] - **Flexion/ Extension** ○ 0.05 Nm/° – 0.26 Nm/° (males, flexion) **0.04** Nm/° - 0.19 Nm/° (females, flexion) ○ **0.03** Nm/° - 0.30 Nm/° (males, extension) **0.01** Nm/° - 0.26 Nm/° (females, extension) [34] - **Axial rotation** ○ 0.054-0.124 Nm/° (rotation to the right) ○ 0.053-0.115 Nm/° (rotation to the left) [37]	- **Lateral flexion** ○ 0.05 Nm/° – 0.29 Nm/° (males, to the right) **0.03** Nm/° - 0.19 Nm/° (females, to the right) ○ **0.05** Nm/° - 0.31 Nm/° (males, to the left) **0.03** Nm/° - 0.20 Nm/° (females, to the left) [34] - **Flexion/ Extension** ○ 0.05 Nm/° – 0.26 Nm/° (males, flexion) **0.04** Nm/° - 0.19 Nm/° (females, flexion) ○ **0.03** Nm/° - 0.30 Nm/° (males, extension) **0.01** Nm/° - 0.26 Nm/° (females, extension) [34] - **Axial rotation** ○ 0.054-0.124 Nm/° (rotation to the right) ○ 0.053-0.115 Nm/° (rotation to the left) [37] - **Anterior/ Posterior translation** ○ Anterior translation: 62 N/mm ○ Posterior translation: 50 N/mm [38, 39] - **Lateral translation** ○ 73 N/mm [38, 39] - **Vertical tensional/ Vertical compressional translation** ○ Vertical tensional translation: 68 N/mm [38, 40] ○ Vertical compressional translation: 822-2931 [38, 41, 42]
Thoracic and Lumbar spine	Stiff	- **Flexion/ Extension** ○ **0.29** Nm/° - 1.34 Nm/° (lumbar spine, flexion) ○ **0.17** Nm/° **– 0.86** Nm/° (lumbar spine, extension) [35]	- **Lateral flexion** ○ 0.32 Nm/° - 2.16 Nm/° (lumbar spine) [35] - **Flexion/ Extension** ○ **0.29** Nm/° - 1.34 Nm/° (lumbar spine, flexion) ○ **0.17** Nm/° **– 0.86** Nm/° (lumbar spine, extension) [35] - **Rotation** ○ 0.13 Nm/° - 0.64 Nm/° [35]

Appendix A.4.

Mass of infant bodies and mass of body segments

Table 1. Overview of the body mass, proportional segment mass and total segment mass of male infants [3, 4, 45]. The mass of the various segments is calculated by the use of the polynomial regression function developed by R.K. Jensen (1989) and validated by R.M.H.P. van Haaster (1995) for the age range of 0-4 years [3, 4]. In this polynomial regression function the total body mass, derived from the age-length and mass-length figures obtained by TNO (2010) [45], are filled in together with specific ages, which are corresponding to the age ranges applied for the dimensions of Appendix A.1.,Table 1.

Body part	Age (months/ years) / Body part and variable (unit)	1/ 0.083	3/ 0.25	6/ 0.5	9/ 0.75	12/ 1.0	16/ 1.333	18/ 1.5	20/ 1.667	24/ 2.0	30/ 2.5	36/ 3.0	42/ 3.5
Total body	Length (cm)	54.7	60.9	68.0	72.9	76.7	81.0	82.8	84.7	88.4	93.5	97.8	101.7
	Mass (kg)	4.3	5.8	7.6	9.0	10.3	11.3	11.6	12.1	13.0	14.1	15.3	16.3
	SD (kg)	0.4	0.5	0.6	0.7	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.2
Head + neck	Proportional segmental mass (-)	2.8 E-1	2.8 E-1	2.7 E-1	2.6 E-1	2.6 E-1	2.5 E-1	2.5 E-1	2.5 E-1	2.4 E-1	2.3 E-1	2.2 E-1	2.1 E-1
	Total segmental mass (kg)	1.2	1.6	2.0	2.4	2.7	2.8	2.9	3.0	3.1	3.2	3.4	3.4
Torso	Proportional segmental mass (-)	4.8 E-1	4.7 E-1	4.7 E-1	4.7 E-1	4.6 E-1	4.6 E-1	4.6 E-1	4.6 E-1	4.5 E-1	4.5 E-1	4.5 E-1	4.4 E-1
	Total segmental mass (kg)	2.0	2.7	3.6	4.2	4.8	5.2	5.3	5.5	5.9	6.3	6.8	7.2
Upper arm	Proportional segmental mass (-)	2.3 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.5 E-2	2.5 E-2	2.6 E-2	2.6 E-2
	Total segmental mass (kg)	1.0 E-1	1.4 E-1	1.8 E-1	2.2 E-1	2.5 E-1	2.8 E-1	2.8 E-1	3.0 E-1	3.2 E-1	3.6 E-1	3.9 E-1	4.2 E-1
Forearm	Proportional Segmental mass (-)	1.3 E-2	1.3 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2
	Total segmental mass (kg)	5.8 E-2	7.8 E-2	1.0 E-1	1.2 E-1	1.4 E-1	1.6 E-1	1.6 E-1	1.7 E-1	1.8 E-1	2.0 E-1	2.2 E-1	2.4 E-1
Hand	Proportional segmental mass (-)	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3
	Total segmental mass (kg)	3.8 E-2	5.1 E-2	6.7 E-2	7.9 E-2	9.1 E-2	9.9 E-2	1.0 E-1	1.1 E-1	1.1 E-1	1.2 E-1	1.3 E-1	1.4 E-1
Thigh	Proportional segmental mass (-)	4.4 E-2	4.5 E-2	4.7 E-2	5.0 E-2	5.2 E-2	5.4 E-2	5.6 E-2	5.6 E-2	6.0 E-2	6.4 E-2	6.7 E-2	7.1 E-2
	Total segmental mass (kg)	1.9 E-1	2.6 E-1	3.6 E-1	4.5 E-1	5.3 E-1	6.2 E-1	6.5 E-1	6.9 E-1	7.8 E-1	9.0 E-1	1.0	1.2
Calf	Proportional segmental mass (-)	2.2 E-2	2.3 E-2	2.4 E-2	2.5 E-2	2.6 E-2	2.8 E-2	2.9 E-2	2.9 E-2	3.1 E-2	3.3 E-2	3.5 E-2	3.6 E-2
	Total segmental mass (kg)	9.5 E-2	1.3 E-1	1.8 E-1	2.3 E-1	2.7 E-1	3.2 E-1	3.3 E-1	3.5 E-1	4.0 E-1	4.6 E-1	5.3 E-1	5.9 E-1
Foot	Proportional segmental mass (-)	1.4 E-2	1.4 E-2	1.4 E-2	1.5 E-2	1.5 E-2	1.5 E-2	1.6 E-2	1.6 E-2	1.6 E-2	1.7 E-2	1.7 E-2	1.8 E-2
	Total segmental mass (kg)	5.9 E-2	8.1 E-2	1.1 E-1	1.3 E-1	1.5 E-1	1.7 E-1	1.8 E-1	1.9 E-1	2.1 E-1	2.4 E-1	2.6 E-1	2.9 E-1

Table 2. Overview of the body mass, proportional segment mass and total segment mass of female infants [3, 4, 46]. The mass of the various segments is calculated by the use of the polynomial regression function developed by R.K. Jensen (1989) and validated by R.M.H.P. van Haaster (1995) for the age range of 0-4 years [3, 4]. In this polynomial regression function the total body mass, derived from the age-length and mass-length figures obtained by TNO (2010) [46], are filled in together with specific ages, which are corresponding to the age ranges applied for the dimensions of Appendix A.1,Table 1.

Body part and variable	Age (months/ years)	1/ 0.083	3/ 0.25	6/ 0.5	9/ 0.75	12/ 1.0	16/ 1.333	18/ 1.5	20/ 1.667	24/ 2.0	30/ 2.5	36/ 3.0	42/ 3.5
Total body	Length (cm)	54.0	59.6	66.4	71.2	75.0	79.5	81.5	83.4	87.1	92.2	97.0	101.3
	Mass (kg)	4.1	5.4	7.2	8.5	9.5	10.6	11.1	11.5	12.3	13.6	14.7	15.9
	SD (kg)	0.4	0.5	0.6	0.7	0.8	0.8	0.8	0.9	0.9	1.0	1.1	1.2
Head + neck	Proportional segmental mass (-)	2.8 E-1	2.7 E-1	2.7 E-1	2.6 E-1	2.6 E-1	2.5 E-1	2.5 E-1	2.5 E-1	2.4 E-1	2.3 E-1	2.2 E-1	2.1 E-1
	Total segmental mean mass (kg)	1.1	1.5	1.9	2.2	2.5	2.7	2.8	2.8	2.9	3.1	3.2	3.4
Torso	Proportional segmental mass (-)	4.8 E-1	4.7 E-1	4.7 E-1	4.7 E-1	4.6 E-1	4.6 E-1	4.6 E-1	4.6 E-1	4.5 E-1	4.5 E-1	4.5 E-1	4.4 E-1
	Total segmental mean mass (kg)	1.9	2.6	3.4	4.0	4.4	4.9	5.1	5.3	5.6	6.1	6.5	7.0
Upper arm	Proportional segmental mass (-)	2.3 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.4 E-2	2.5 E-2	2.5 E-2	2.6 E-2	2.6 E-2
	Total segmental mean mass (kg)	9.6 E-2	1.3 E-1	1.7 E-1	2.0 E-1	2.3 E-1	2.6 E-1	2.7 E-1	2.8 E-1	3.1 E-1	3.4 E-1	3.8 E-1	4.1 E-1
Fore-arm	Proportional segmental mass (-)	1.3 E-2	1.3 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2	1.4 E-2
	Total segmental mean mass (kg)	5.5 E-2	7.3 E-2	9.8 E-2	1.2 E-1	1.3 E-1	1.5 E-1	1.5 E-1	1.6 E-1	1.7 E-1	1.9 E-1	2.1 E-1	2.3 E-1
Hand	Proportional segmental mass (-)	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3	8.8 E-3
	Total segmental mean mass (kg)	3.6 E-2	4.8 E-2	6.3 E-2	7.5 E-2	8.4 E-2	9.3 E-2	9.8 E-2	1.0 E-1	1.1 E-1	1.2 E-1	1.3 E-1	1.4 E-1
Thigh	Proportional segmental mass (-)	4.4 E-2	4.5 E-2	4.7 E-2	5.0 E-2	5.2 E-2	5.4 E-2	5.6 E-2	5.6 E-2	6.0 E-2	6.4 E-2	6.7 E-2	7.1 E-2
	Total segmental mean mass (kg)	1.8 E-1	2.4 E-1	3.4 E-1	4.2 E-1	4.9 E-1	5.8 E-1	6.2 E-1	6.6 E-1	7.4 E-1	8.7 E-1	9.9 E-1	1.1
Calf	Proportional segmental mass (-)	2.2 E-2	2.3 E-2	2.4 E-2	2.5 E-2	2.6 E-2	2.8 E-2	2.9 E-2	2.9 E-2	3.1 E-2	3.3 E-2	3.5 E-2	3.6 E-2
	Total segmental mean mass (kg)	9.1 E-2	1.2 E-1	1.7 E-1	2.2 E-1	2.5 E-1	3.0 E-1	3.2 E-1	3.4 E-1	3.8 E-1	4.4 E-1	5.1 E-1	5.8 E-1
Foot	Proportional segmental mass (-)	1.4 E-2	1.4 E-2	1.4 E-2	1.5 E-2	1.5 E-2	1.5 E-2	1.6 E-2	1.6 E-2	1.6 E-2	1.7 E-2	1.7 E-2	1.8 E-2
	Total segmental mean mass (kg)	5.6 E-2	7.5 E-2	1.0 E-1	1.2 E-1	1.4 E-1	1.6 E-1	1.7 E-1	1.8 E-1	2.0 E-1	2.3 E-1	2.5 E-1	2.8 E-1

Appendix A.5.

Approximation of segmental radius of gyration and segmental moment of inertia of infant bodies

Table 1. Overview of the approximation of the proportional segmental radius of gyration, the segmental radius of gyration and the total segment inertia of bodies of male infants [3, 4, 45].
The proportional segmental radius of gyration of various segments (transverse axis of gyration) is calculated by the use of the polynomial regression function developed by R.K. Jensen (1989) and validated by R.M.H.P. van Haaster (1995) for the age range of 0-4 years [3, 4]. In this polynomial regression function, the total body mass, derived from the age-length and mass-length figures obtained by TNO (2010) [45], are filled in together with specific ages, which are corresponding to the age ranges applied for the dimensions of Appendix A.1, Table 1. In this way the proportional segmental radius for various ages are calculated. Then this is multiplied to the segment length of the various body segments. These segment lengths are originating from Appendix A.1, Table 1 and Table 2. If the specific age was not mentioned there, an approximation of the length was made. When separate male and female data was available, this data was used. In this way the segment radius of gyration has been calculated. To be able to calculate the total segmental inertia, the segmental mass from Appendix A.4, Table 1 was multiplied with the squared calculated segment radius of gyration, as described by R.K. Jensen (1989) and R.M.H.P. van Haaster (1995) [3, 4]. The segment radius of gyration is defined from the proximal side and for the torso from the shoulder joint.

Body part and variable	Age (months/ years)	1/ 0.083	3/ 0.25	6/ 0.5	9/ 0.75	12/ 1.0	16/ 1.333	(18)/ 1.5	20/ 1.667	24/ 2.0	(30)/ 2.5	(36)/ 3.0	42/ 3.5
Total body	Length	54.7	60.9	68.0	72.9	76.7	81.0	82.8	84.7	88.4	93.5	97.8	101.7
	Mass (kg)	4.3	5.8	7.6	9.0	10.3	11.3	11.6	12.1	13.0	14.1	15.3	16.3
	SD (kg)	0.4	0.5	0.6	0.7	0.8	0.9	0.9	0.9	1.0	1.0	1.1	1.2
Head + neck (Shoulder to head length) (Table 2)	Proportional segmental radius of gyration (-)	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1
	Segment length (m)	0.143	0.160	0.164	0.175	0.188	0.174	0.185	0.178	0.204	0.200	0.213	0.208
	Segment radius of gyration (m)	4.4 E-2	4.9 E-2	5.0 E-2	5.4 E-2	5.8 E-2	5.4 E-2	5.7 E-2	5.5 E-2	6.3 E-2	6.2 E-2	6.5 E-2	6.4 E-2
	Total segmental inertia	2.3 E-3	3.8 E-3	5.2 E-3	6.9 E-3	8.9 E-3	8.1 E-3	9.3 E-3	8.9 E-3	1.2 E-2	1.2 E-2	1.4 E-2	1.4 E-2
Torso (crown-rump length) – (shoulder to head length) (Table 2)	Proportional segmental radius of gyration (-)	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1
	Segment length (m)	0.244	0.266	0.289	0.302	0.317	0.319	0.335	0.323	0.329	0.346	0.351	0.373
	Segment radius of gyration (m)	7.3 E-2	8.0 E-2	8.7 E-2	9.0 E-2	9.5 E-2	9.6 E-2	1.0 E-1	9.7 E-2	9.9 E-2	1.0 E-1	1.1 E-1	1.1 E-1
	Total segmental inertia	1.1 E-2	1.7 E-2	2.7 E-2	3.4 E-2	4.3 E-2	4.8 E-2	5.4 E-2	5.2 E-2	5.7 E-2	6.8 E-2	7.5 E-2	9.0 E-2
Upper arm (shoulder-Elbow Length) (Table 1)	Proportional segmental radius of gyration (-)	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1
	Segment length (m)	0.109	0.113	0.119	0.135	0.139	0.146	0.154	0.152	0.174	0.181	0.195	0.202
	Segment radius of gyration (m)	3.5 E-2	3.6 E-2	3.8 E-2	4.3 E-2	4.4 E-2	4.6 E-2	4.9 E-2	4.8 E-2	5.5 E-2	5.7 E-2	6.2 E-2	6.4 E-2
	Total segmental inertia	1.2 E-4	1.8 E-4	2.6 E-4	4.0 E-4	4.9 E-4	5.9 E-4	6.8 E-4	6.9 E-4	9.8 E-3	1.2 E-3	1.5 E-3	1.7 E-3
Forearm	Proportional segmental	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1

Body part and variable	Age (months/ years)	1/ 0.083	3/ 0.25	6/ 0.5	9/ 0.75	12/ 1.0	16/ 1.333	(18)/ 1.5	20/ 1.667	24/ 2.0	(30)/ 2.5	(36)/ 3.0	42/ 3.5
(Mean elbow-hand length) – (mean hand length) (Table 1)	radius of gyration (-)												
	Segment length (m)	0.081	0.092	0.10	0.107	0.107	0.114	0.114	0.12	0.141	0.141	0.141	0.141
	Segment radius of gyration (m)	2.4 E-2	2.7 E-2	2.9 E-2	3.1 E-2	3.1 E-2	3.3 E-2	3.3 E-2	3.5 E-2	4.1 E-2	4.1 E-2	4.1 E-2	4.1 E-2
	Total segment inertia	3.3 E-5	5.7 E-5	8.9 E-5	1.2 E-4	1.4 E-4	1.7 E-4	1.8 E-4	2.1 E-4	3.1 E-4	3.4 E-4	3.7 E-4	4.0 E-4
Hand	Proportional segmental radius of gyration (-)	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1
	Segment length (m)	0.068	0.068	0.075	0.083	0.086	0.087	0.093	0.089	0.099	0.103	0.111	0.115
	Segment radius of gyration (m)	1.6 E-2	1.6 E-2	1.8 E-2	2.0 E-2	2.1 E-2	2.1 E-2	2.2 E-2	2.1 E-2	2.4 E-2	2.5 E-2	2.6 E-2	2.7 E-2
	Total segmental inertia	1.0 E-5	1.3 E-5	2.1 E-5	3.1 E-5	3.8 E-5	4.3 E-5	5.0 E-5	4.8 E-5	6.4 E-5	7.5 E-5	9.4 E-5	1.1 E-4
Thigh (rump knee length) (Table 1)	Proportional segmental radius of gyration (-)	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1
	Segment length (m)	0.139	0.142	0.157	0.175	0.183	0.196	0.213	0.202	NA	NA	NA	NA
	Segmental radius of gyration (m)	4.0 E-2	4.1 E-2	4.6 E-2	5.1 E-2	5.3 E-2	5.7 E-2	6.2 E-2	5.9 E-2	NA	NA	NA	NA
	Total segmental inertia	3.1 E-4	4.5 E-4	7.5 E-4	1.2 E-3	1.5 E-3	2.0 E-3	2.5 E-3	2.4 E-3	NA	NA	NA	NA
Calf (knee-sole length, tibiale height) (Table 1)	Proportional segmental radius of gyration (-)	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1
	Segment length (m)	0.149	0.154	0.171	0.183	0.198	0.203	0.216	0.214	0.201	0.21	0.228	0.237
	Segmental radius of gyration (m)	4.4 E-2	4.5 E-2	5.0 E-2	5.3 E-2	5.8 E-2	5.9 E-2	6.3 E-2	6.2 E-2	5.9 E-2	6.1 E-2	6.6 E-2	6.9 E-2
	Total segmental inertia	1.8 E-4	2.7 E-4	4.6 E-4	6.5 E-4	9.1 E-4	1.1 E-3	1.3 E-3	1.4 E-3	1.4 E-3	1.7 E-3	2.3 E-3	2.8 E-3
Foot	Proportional segmental radius of gyration (-)	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1
	Segment length (m)	0.082	0.085	0.093	0.103	0.109	0.109	0.119	0.116	0.139	0.145	0.155	0.161
	Segmental radius of gyration	2.0 E-2	2.1 E-2	2.3 E-2	2.5 E-2	2.7 E-2	2.7 E-2	2.9 E-2	2.8 E-2	3.4 E-2	3.5 E-2	3.8 E-2	3.9 E-2
	Total segmental inertia	2.3 E-5	3.5 E-5	5.6 E-5	8.3 E-5	1.1 E-4	1.2 E-4	1.5 E-4	1.5 E-4	2.4 E-4	3.0 E-4	3.8 E-4	4.5 E-4

Table 2. Overview of the approximation of the proportional segmental radius of gyration, the segmental radius of gyration and the total segment inertia of bodies of female infants [3, 4, 46].

The proportional segmental radius of gyration of various segments (transverse axis of gyration) is calculated by the use of the polynomial regression function developed by R.K. Jensen (1989) and validated by R.M.H.P. van Haaster (1995) for the age range of 0-4 years [3, 4]. In this polynomial regression function, the total body mass, derived from the age-length and mass-length figures obtained by TNO (2010)[45, 46], are filled in together with specific ages, which are corresponding to the age ranges applied for the dimensions of Appendix A.1, Table 1. In this way the proportional segmental radius for various ages are calculated. Then this is multiplied to the segment length of the various body segments. These segment lengths are originating from Appendix A.1, Table 1 and Table 2. If the specific age was not mentioned there, an approximation of the length was made. When separate male and female data was available, this data was used. In this way the segment radius of gyration has been calculated. To be able to calculate the total segmental inertia, the segmental mass from Appendix A.4, Table 1 was multiplied with the squared calculated segment radius of gyration, as described by R.K. Jensen (1989) and R.M.H.P. van Haaster (1995) [3, 4]. The segment radius of gyration is defined from the proximal side and for the torso from the shoulder joint.

Body part and variables	Age (months/ years)	1/ 0.083	3/ 0.25	6/ 0.5	9/ 0.75	12/ 1.0	16/ 1.333	18/ 1.5	20/ 1.667	24/ 2.0	30/ 2.5	36/ 3.0	42/ 3.5
Total body	Length (cm)	54.0	59.6	66.4	71.2	75.0	79.5	81.5	83.4	87.1	92.2	97.0	101.3
	Mass (kg)	4.1	5.4	7.2	8.5	9.5	10.6	11.1	11.5	12.3	13.6	14.7	15.9
	SD (kg)	0.4	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.2
Head + neck (Shoulder to head length) (Table 2)	Proportional segmental radius of gyration (-)	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1	3.1 E-1
	Segment length (m)	0.143	0.160	0.164	0.175	0.188	0.174	0.185	0.178	0.204	0.200	0.213	0.208
	Segment radius of gyration (m)	4.4 E-2	4.9 E-2	5.0 E-2	5.4 E-2	5.8 E-2	5.4 E-2	5.7 E-2	5.5 E-2	6.3 E-2	6.2 E-2	6.5 E-2	6.4 E-2
	Total segmental inertia ($kg*m^2$)	2.2 E-3	3.6 E-3	4.9 E-3	6.5 E-3	8.2 E-3	7.6 E-3	8.9 E-3	8.4 E-3	1.2 E-2	1.2 E-2	1.4 E-2	1.4 E-2
Torso (crown-rump length) – (shoulder to head length) (Table 2)	Proportional segmental radius of gyration (-)	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1	3.0 E-1
	Segment length (m)	0.244	0.266	0.289	0.302	0.317	0.319	0.335	0.323	0.329	0.346	0.351	0.373
	Segment radius of gyration (m)	7.3 E-2	8.0 E-2	8.7 E-2	9.0 E-2	9.5 E-2	9.6 E-2	1.0 E-1	9.7 E-2	9.9 E-2	1.0 E-1	1.1 E-1	1.1 E-1
	Total segmental inertia ($kg*m^2$)	1.0 E-2	1.6 E-2	2.5 E-2	3.3 E-2	4.0 E-2	4.5 E-2	5.1 E-2	4.9 E-2	5.4 E-2	6.6 E-2	7.2 E-2	8.8 E-2
Upper arm (shoulder - Elbow Length) (Table 1)	Proportional segmental radius of gyration (-)	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1	3.2 E-1
	Segment length (m)	0.109	0.113	0.119	0.135	0.139	0.146	0.154	0.152	0.169	0.176	0.188	0.195
	Segment radius of gyration (m)	3.5 E-2	3.6 E-2	3.8 E-2	4.3 E-2	4.4 E-2	4.6 E-2	4.9 E-2	4.8 E-2	5.4 E-2	5.6 E-2	5.9 E-2	6.2 E-2
	Total segmental inertia ($kg*m^2$)	1.2 E-4	1.7 E-4	2.5 E-4	3.8 E-4	4.5 E-4	5.6 E-4	6.5 E-4	6.6 E-4	8.8 E-4	1.1 E-3	1.3 E-3	1.6 E-3
Forearm (Mean elbow-	Proportional segmental radius of gyration (-)	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1

Age (months/ years) / Body part and variables		1/ 0.083	3/ 0.25	6/ 0.5	9/ 0.75	12/ 1.0	16/ 1.333	18/ 1.5	20/ 1.667	24/ 2.0	30/ 2.5	36/ 3.0	42/ 3.5
hand length) – (mean hand length) (Table 1)	Segment length (m)	0.081	0.092	0.10	0.107	0.107	0.114	0.114	0.12	0.137	0.137	0.137	0.137
	Segment radius of gyration (m)	2.4 E-2	2.7 E-2	2.9 E-2	3.1 E-2	3.1 E-2	3.3 E-2	3.3 E-2	3.5 E-2	4.0 E-2	4.0 E-2	4.0 E-2	4.0 E-2
	Total segmental inertia (kg*m²)	3.1 E-5	5.3 E-5	8.4 E-5	1.1 E-4	1.3 E-4	1.6 E-4	1.7 E-4	2.0 E-4	2.8 E-4	3.1 E-4	3.4 E-4	3.7 E-4
Hand	Proportional segmental radius of gyration (-)	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1
	Segment length (m)	0.068	0.068	0.075	0.083	0.086	0.087	0.093	0.089	0.097	0.100	0.106	0.109
	Segment radius of gyration (m)	1.6 E-2	1.6 E-2	1.8 E-2	2.0 E-2	2.1 E-2	2.1 E-2	2.2 E-2	2.1 E-2	2.3 E-2	2.4 E-2	2.5 E-2	2.6 E-2
	Total segmental inertia (kg*m²)	9.5 E-6	1.3 E-5	2.0 E-5	2.9 E-5	3.5 E-5	4.0 E-5	4.8 E-5	4.6 E-5	5.8 E-5	6.8 E-5	8.3 E-5	9.5 E-5
Thigh (rump knee length) (Table 1)	Proportional segmental radius of gyration (-)	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1
	Segment length (m)	0.139	0.142	0.157	0.175	0.183	0.196	0.213	0.202	NA	NA	NA	NA
	Segment radius of gyration (m)	4.0 E-2	4.1 E-2	4.6 E-2	5.1 E-2	5.3 E-2	5.7 E-2	6.2 E-2	5.9 E-2	NA	NA	NA	NA
	Total segmental inertia (kg*m²)	2.9 E-4	4.2 E-4	7.1 E-4	1.1 E-3	1.4 E-3	1.9 E-3	2.4 E-3	2.3 E-3	NA	NA	NA	NA
Calf (knee-sole length, tibiale height) (Table 1)	Proportional segmental radius of gyration (-)	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1	2.9 E-1
	Segment length (m)	0.149	0.154	0.171	0.183	0.198	0.203	0.216	0.214	0.208	0.218	0.236	0.246
	Segment radius of gyration (m)	4.4 E-2	4.5 E-2	5.0 E-2	5.3 E-2	5.8 E-2	5.9 E-2	6.3 E-2	6.2 E-2	6.1 E-2	6.3 E-2	6.9 E-2	7.1 E-2
	Total segmental inertia (kg*m²)	1.7 E-4	2.5 E-4	4.3 E-4	6.1 E-4	8.4 E-4	1.0 E-3	1.3 E-3	1.3 E-3	1.4 E-3	1.8 E-3	2.4 E-3	3.0 E-3
Foot	Proportional segmental radius of gyration (-)	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1	2.4 E-1
	Segment length (m)	0.082	0.085	0.093	0.103	0.109	0.109	0.119	0.116	0.135	0.14	0.15	0.155
	Segment radius of gyration (m)	2.0 E-2	2.1 E-2	2.3 E-2	2.5 E-2	2.7 E-2	2.7 E-2	2.9 E-2	2.8 E-2	3.3 E-2	3.4 E-2	3.7 E-2	3.8 E-2
	Total segmental inertia (kg*m²)	2.2 E-5	3.2 E-5	5.3 E-5	7.8 E-5	1.0 E-4	1.2 E-4	1.5 E-4	1.5 E-4	2.2 E-4	2.7 E-4	3.4 E-4	4.0 E-4

Appendix A.6.

Locations of centre of masses of various body parts

Table 1. Overview of locations of centre of masses [%] of total joint, measured from proximal side [5].

Body part	Location of centre of mass
Thigh	48.59 ± 1.69%
Leg	43.77 ± 0.86%
Foot	34.69 ± 2.74%
Upper arm	44.28 ± 1.39%
Forearm	45.41 ± 0.78%
Hand	44.95 ± 9.03%

Appendix A.7.
Mechanical and material properties of bridging veins

Table 1. Ultimate stress (MPa) at various strain rates (Hz) [2, 9].

Source	Method	Age range	Post-mortem time	Strain rate (Hz)		
				1.677 ± 0.242	15.692 ± 3.446	Post cyclic (2.747 ± 0.384)
Pasquesi, 2017	Pulling device	0 – 12 months	< 24 hours	7.204 ± 4.613	9.885 ± 6.725	7.645 ± 4.755

Table 2. Ultimate strain (%) at various strain rates (Hz) [2, 9].

Source	Method	Age range	Post-mortem time	Strain rate (Hz)		
				1.677 ± 0.242	15.692 ± 3.446	Post cyclic (2.747 ± 0.384)
Pasquesi, 2017	Pulling device	0 – 12 months	< 24 hours	48.9 ± 18.3	42.8 ± 17.2	42.7 ± 13.4

Table 3. Stress-strain behaviour [2, 9].

	Yield strain (stretch)	Yield stress (Mpa)	Ultimate strain (stretch)	Ultimate stress (Mpa)
Low strain rate (1.677 ± 0.242 Hz)	1.240 ± 0.085	5.424 ± 4.252	1.489 ± 0.183	7.204 ± 4.613
High strain rate (15.692 ± 3.446 Hz)	1.256 ± 0.065	7.837 ± 6.240	1.428 ± 0.172	9.885 ± 6.752
Post-cyclic (2.747 ± 0.384 Hz)	1.296 ± 0.052	5.758 ± 4.479	1.427 ± 0.134	7.645 ± 4.755

Table 4. Elastic moduli (Mpa) at various strain rates (Hz) [2, 9].

	Elastic modulus (Mpa)
Low strain rate (1.677 ± 0.242 Hz)	30.173 ± 18.492
High strain rate (15.692 ± 3.446 Hz)	49.044 ± 39.764
Post-cyclic (2.747 ± 0.384 Hz)	48.106 ± 32.908

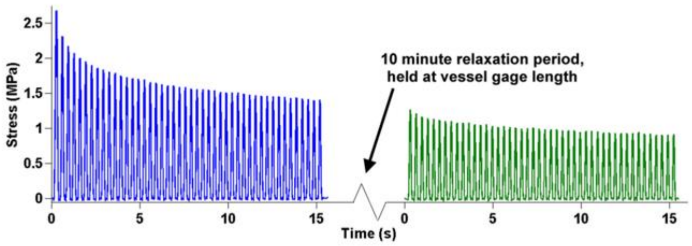


Figure 1. Relaxation behaviour of bridging veins [2, 9].

Table 5. Intraocular pressure (mmHg) of the eye at various ages [11].

Age	<1	1	2	3
Arithmetic mean (mmHg)	8.9	9.8	10.4	11.5
Mean, standard deviation	2.4	2.7	1.2	1.7

Table 6. Mechanical and material properties of the human eye [12].

Eye part	Elastic modulus (MPa)	Poisson's ratio	Density (kg/m^3)
Cornea	6.1	0.494	1400
Aqueous humor	0.037	0.49	999
Iris	0.5	0.49	1100
Ciliary body	11	0.4	1600
Lens	1.5	0.49	315
Vitreous humor	0.042	0.49	999
Choroid	0.03	0.49	999
Sclera	48	0.454	1400

Appendix A.8.
Mechanical and material properties of brain tissue

Table 1. Shear storage moduli (Pa) at various frequencies (Hz) [2, 13].

Source	Test	Material	Frequencies (Hz)		
			0.1	1	10
Chatelin et al., 2012	Dynamic oscillatory shear experiments (2 and 5 months old human infants)	Brain stem	1100 ± 180	1480 ± 420	1700 ± 400
		Grey matter	400 ± 80	550 ± 80	700 ± 90
		White matter	340 ± 30	410 ± 30	700 ± 90

Table 2. Shear loss moduli (Pa) at various frequencies (Hz) [2, 13].

Source	Test	Material	Frequencies (Hz)		
			0.1	1	10
Chatelin et al., 2012	Dynamic oscillatory shear experiments (2 and 5 months old human infants)	Brain stem	260 ± 45	290 ± 75	500 ± 50
		Grey matter	105 ± 5	115 ± 5	250 ± 20
		White matter	80 ± 10	91 ± 10	200 ± 10

Table 3. Complex moduli (Pa) at various frequencies (Hz) or indentation times (ms) [1, 2, 14].

Source	Method	Age category	Brain region	Frequency (Hz)	Indentation time (ms)	Complex modulus (Pa)
Finan et al., 2017	Micro indentation	7 – 58 years	Cortical white matter		10	1085 ± 205
					50	600 ± 120
					20.000	150 ± 40
		4 – 58 years	Cortical grey matter		10	620 ± 25
					50	400 ± 10
					20.000	100 ± 10
		5 – 58 years	Hippocampus		10	1080 ± 140
					50	700 ± 100
					20.000	180 ± 25
Yeung et al., 2019	Magnetic resonance elastography	7 – 44 years children (7 – 12 years), adolescents (13 – 18 years), adults (18 – 44 years)	White matter	30		1110 ± 140, 1110 ± 140, 1130 ± 130
				40		1470 ± 250, 1520 ± 140, 1640 ± 190
				60		2150 ± 300, 2240 ± 140, 2330 ± 260
		7 – 44 years children (7 – 12 years), adolescents (13 – 18 years), adults (18 – 44 years)	Grey matter	30		1080 ± 120, 1060 ± 120, 1060 ± 140
				40		1470 ± 220, 1520 ± 110, 1510 ± 190
				60		2150 ± 300, 2240 ± 190, 2230 ± 240

Table 4. Shear stiffness (kPa) of various brain regions at two age categories [2, 15].

Region	Adolescent	Adult
Cerebrum	3.13 ± 0.31	3.23 ± 0.21
Cerebellum	2.48 ± 0.27	2.74 ± 0.21
Frontal Lobe	2.97 ± 0.32	3.11 ± 0.26
Occipital Lobe	2.80 ± 0.25	2.76 ± 0.26
Parietal Lobe	2.84 ± 0.37	3.12 ± 0.52
Temporal Lobe	3.01 ± 0.25	3.16 ± 0.30
Deep GM/WM	3.49 ± 0.44	3.45 ± 0.25
Amygdala	3.49 ± 0.41	3.59 ± 0.32
Hippocampus	3.25 ± 0.55	3.35 ± 0.30
Caudate	4.11 ± 0.40	3.83 ± 0.17
Putamen	4.00 ± 0.32	3.83 ± 0.22
Pallidum	3.96 ± 0.36	3.84 ± 0.21
Thalamus	4.02 ± 0.34	3.96 ± 0.24

Table 5. Damping ratio of various brain regions at two age categories [2, 15].

Region	Adolescent	Adult
Cerebrum	0.225 ± 0.021	0.222 ± 0.018
Cerebellum	0.286 ± 0.050	0.260 ± 0.042
Frontal Lobe	0.216 ± 0.022	0.235 ± 0.029
Occipital Lobe	0.269 ± 0.061	0.271 ± 0.039
Parietal Lobe	0.247 ± 0.034	0.243 ± 0.040
Temporal Lobe	0.237 ± 0.034	0.220 ± 0.024
Deep GM/WM	0.218 ± 0.024	0.208 ± 0.019
Amygdala	0.228 ± 0.039	0.215 ± 0.032
Hippocampus	0.188 ± 0.032	0.187 ± 0.030
Caudate	0.205 ± 0.028	0.221 ± 0.017
Putamen	0.209 ± 0.020	0.221 ± 0.010
Pallidum	0.199 ± 0.017	0.203 ± 0.018
Thalamus	0.192 ± 0.019	0.187 ± 0.012

Table 6. Elasticity score of various brain regions of neonates (28-40 weeks old) [2, 16].

Intracranial Structure	Elasticity Score (range)
Ventricle	1.0 (1.00 – 1.00)
Subdural space	1.0 (1.00 – 1.00)
Periventricular white matter	4.0 (3.00 – 4.00)
Caudate	4.3 (3.67 – 4.67)
Subcortical white matter	4.0 (4.00 – 4.00)
Cortical grey matter	3.0 (2.33 – 3.33)

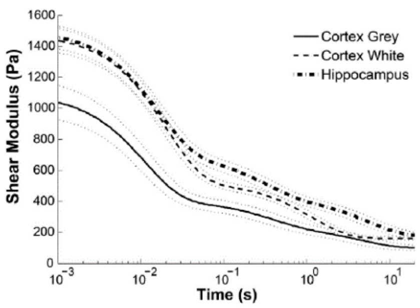


Figure 1. Relaxation behaviour of grey and white cortex and hippocampus [1, 2].

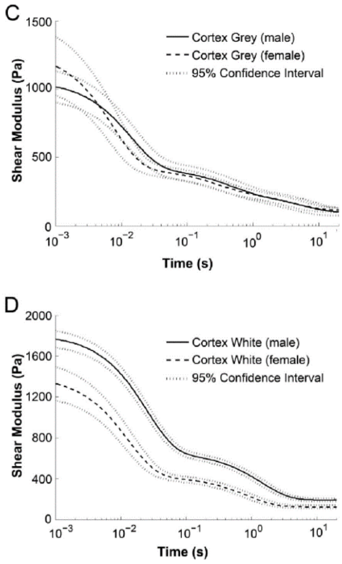


Figure 2. Relaxation behaviour of grey and white cortex for females and males [1, 2].

Table 7. Overview of the volume (mm^3) of various brain regions [17].

Region	Neonate	1 year old	2 years old
TBV	425.387 ± 4806	855.540 ± 12.492	983.866 ± 15.393
Cerebral hemispheres	370.685 ± 4185	699.378 ± 10.199	804.501 ± 12.577
Cerebellum	26.985 ± 371	91.962 ± 1712	105,154 ± 2084
Subcortical + brainstem	27.679 ± 453	64.214 ± 868	73.227 ± 1140
Hemispheric grey	206.480 ± 2396	514.048 ± 6679	588.441 ± 9100
Hemispheric white	164.433 ± 1901	183.280 ± 4122	217.883 ± 5142
Lateral ventricles	2109 ± 149	8069 ± 723	7406 ± 786
Right caudate	NA	3221 ± 69	3778 ± 83
Left caudate	NA	3012 ± 68	3607 ± 91
Right hippocampus	NA	2113 ± 39	2377 ± 65
Left hippocampus	NA	2075 ± 43	2367 ± 68

1. Finan, J.D., et al., *Regional mechanical properties of human brain tissue for computational models of traumatic brain injury.* Acta Biomaterialia, 2017. **55**: p. 333-339.
2. Blom, E.A., *The mechanical and material properties of brain and bridging veins of infants and a comparison to simulant materials - A systematic review*. 2020, TU Delft: Delft.
3. van Haaster, R.M.H.P., *A combined generator for child multibody models*, in *DCT rapporten*. 1995, Technische Universiteit Eindhoven: Eindhoven.
4. Jensen, R.K., *Changes in segment inertia proportions between 4 and 20 years.* Journal of Biomechanics, 1989. **22**(6): p. 529-536.
5. Schneider, K. and R.F. Zernicke, *Mass, center of mass, and moment of inertia estimates for infant limb segments.* Journal of Biomechanics, 1992. **25**(2): p. 145-148.
6. Sakka, L., G. Coll, and J. Chazal, *Anatomy and physiology of cerebrospinal fluid.* European Annals of Otorhinolaryngology, Head and Neck Diseases, 2011. **128**(6): p. 309-316.
7. Lui, A.C.P., T.Z. Polis, and N.J. Cicutti, *Densities of cerebrospinal fluid and spinal anaesthetic solutions in surgical patients at body temperature.* Canadian Journal of Anaesthesia, 1998. **45**(4): p. 297.
8. Bloomfield, I.G., I.H. Johnston, and L.E. Bilston, *Effects of Proteins, Blood Cells and Glucose on the Viscosity of Cerebrospinal Fluid.* Pediatric Neurosurgery, 1998. **28**(5): p. 246-251.
9. Pasquesi, S.A. and S.S. Margulies, *Failure and Fatigue Properties of Immature Human and Porcine Parasagittal Bridging Veins.* Annals of Biomedical Engineering, 2017. **45**(8): p. 1877-1889.
10. Yamazaki, J., M. Yoshida, and H. Mizunuma, *Experimental analyses of the retinal and subretinal haemorrhages accompanied by shaken baby syndrome/abusive head trauma using a dummy doll.* Injury, 2014. **45**(8): p. 1196-1206.
11. Sampaolesi, R.Z., J.; Sampaolesi, J.R., *Normal Intraocular Pressure in Children from Birth to Five Years of Age*, in *The Glaucomas: Volume I - Pediatric Glaucomas*, R. Sampaolesi, J.R. Sampaolesi, and J. Zárate, Editors. 2009, Springer Berlin Heidelberg: Berlin, Heidelberg.
12. Shukla, V., *FEA Investigation of a Human Eye Model Subjected To Intra-Ocular Pressure (IOP) and External Pressure.* Journal of Mechanical Engineering and Applied Mechanics, 2017. **2**: p. 1-14.
13. Chatelin, S., et al., *Towards child versus adult brain mechanical properties.* Journal of the Mechanical Behavior of Biomedical Materials, 2012. **6**: p. 166-173.
14. Yeung, J., et al., *Paediatric brain tissue properties measured with magnetic resonance elastography.* Biomechanics and Modeling in Mechanobiology, 2019. **18**(5): p. 1497-1505.
15. McIlvain, G., et al., *Mechanical properties of the in vivo adolescent human brain.* Developmental Cognitive Neuroscience, 2018. **34**: p. 27-33.
16. Kim, H.G., et al., *Ultrasound elastography of the neonatal brain: Preliminary study*

Journal of Ultrasound in Medicine, 2017. **36**(7): p. 1313-1319.

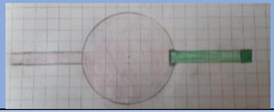
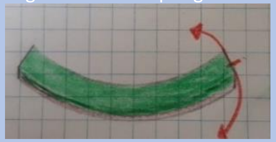
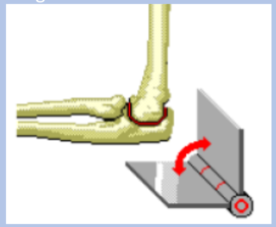
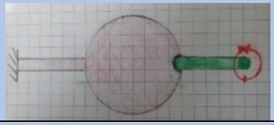
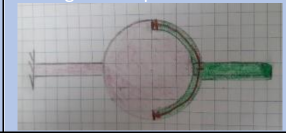
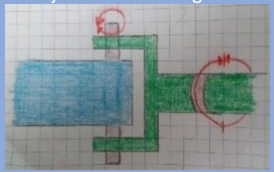
17. Knickmeyer, R.C., et al., *A structural MRI study of human brain development from birth to 2 years.* J Neurosci, 2008. **28**(47): p. 12176-82.
18. Snyder, R.G., *Anthropometry of Infants, Children, and Youths to Age 18 for Product Safety Design. Final Report [microform] / Richard G. Snyder and Others*, ed. A.A.H.S.R.I. Michigan Univ. 1977, [Washington, D.C.]: Distributed by ERIC Clearinghouse.
19. Schneider, L.W., et al. *SIZE AND SHAPE OF THE HEAD AND NECK FROM BIRTH TO FOUR YEARS. FINAL REPORT*. 1986.
20. Schuenke, M., *Thieme atlas of anatomy. General anatomy and musculoskeletal system*. 2nd edition, Latin nomenclature. ed. General anatomy and musculoskeletal system, ed. E. Schulte, et al. 2015, New York, NY: Thieme.
21. Hendriks, H., et al., *Stability of sitting postures: The influence of degrees of freedom.* Ergonomics, 2007. **49**: p. 1611-26.

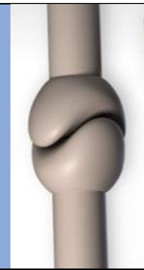
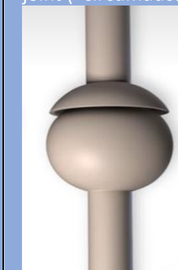
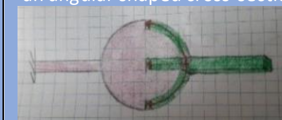
22. Watanabe, H., et al., *[The range of joint motions of the extremities in healthy Japanese people--the difference according to the age (author's transl)].* Nihon Seikeigeka Gakkai Zasshi, 1979. **53**(3): p. 275-61.
23. Reese, N.B., *Joint range of motion and muscle length testing*. 2nd ed ed, ed. W.D. Bandy. 2010, St. Louis, MI: Saunders.
24. Boone, D.C., et al., *Reliability of Goniometric Measurements.* Physical Therapy, 1978. **58**(11): p. 1355-1360.
25. Staheli, L.T., et al., *Lower-extremity rotational problems in children. Normal values to guide management.* J Bone Joint Surg Am, 1985. **67**(1): p. 39-47.
26. Drews, J., J. Vraciu, and G. Pellino, *Range of Motion of the Joints of the Lower Extremities of Newborns.* Physical & Occupational Therapy in Pediatrics, 2009. **4**: p. 49-63.
27. Öhman, A. and E. Beckung, *Reference Values for Range of Motion and Muscle Function of the Neck in Infants.* Pediatric Physical Therapy, 2008. **20**: p. 53-58.
28. Carvalhais, V.O.d.C., et al., *Validity and reliability of clinical tests for assessing hip passive stiffness.* Manual Therapy, 2011. **16**(3): p. 240-245.
29. Chleboun, G.S., et al., *The relationship between elbow flexor volume and angular stiffness at the elbow.* Clinical Biomechanics, 1997. **12**(6): p. 383-392.
30. Formica, D., et al., *The passive stiffness of the wrist and forearm.* Journal of neurophysiology, 2012. **108**: p. 1158-66.
31. McHugh, M. and D. Hogan, *Effect of knee flexion on active joint stiffness.* Acta physiologica Scandinavica, 2004. **180**: p. 249-54.
32. Park, H.S., N.A. Wilson, and L.Q. Zhang, *Gender differences in passive knee biomechanical properties in tibial rotation.* J Orthop Res, 2008. **26**(7): p. 937-44.
33. Roy, A., et al., *Measurement of passive ankle stiffness in subjects with chronic hemiparesis using a novel ankle robot.* Journal of neurophysiology, 2011. **105**(5): p. 2132-2149.
34. McGill, S.M., et al., *Passive stiffness of the human neck in flexion, extension, and lateral bending.* Clinical Biomechanics, 1994. **9**(3): p. 193-198.
35. McGill, S., J. Seguin, and G. Bennett, *Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding.* Spine (Phila Pa 1976), 1994. **19**(6): p. 696-704.
36. Jenny, C., et al., *Biomechanical Response of the Infant Head to Shaking - An Experimental Investigation.* Journal of Neurotrauma, 2016. **34**.
37. Dugailly, P.M., et al., *Assessment of cervical stiffness in axial rotation among chronic neck pain patients: A trial in the framework of a non-manipulative osteopathic management.* Clinical Biomechanics, 2018. **53**: p. 65-71.
38. De Bruijn, E., F. van der Helm, and R. Happee, *Analysis of isometric cervical strength with a nonlinear musculoskeletal model with 48 degrees of freedom.* Multibody System Dynamics, 2015. **34**: p. 1-24.
39. Moroney, S.P., et al., *Load-displacement properties of lower cervical spine motion segments.* J Biomech, 1988. **21**(9): p. 769-79.
40. Pintar, F.A., *Biomechanical Properties of the Human Intervertebral Disk in Tension.* ASME Adv Bioeng, New York, NY. 1986, 1986.
41. De Jager, M.K.J., *Mathematical head-neck models for acceleration impacts.* 1998.
42. Eberlein, R., M. Frohlich, and E.J.C.M.f.R. Hasler, *Finite-element-analyses of intervertebral discs: Recent advances in constitutive modelling.* 1999. **1**: p. 221.
43. Lipps, D.B., et al., *Quantifying the Multidimensional Impedance of the Shoulder During Volitional Contractions.* Annals of Biomedical Engineering, 2020. **48**(9): p. 2354-2369.
44. Panjabi, M.M., et al., *Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves.* Spine (Phila Pa 1976), 2001. **26**(24): p. 2692-700.
45. TNO, *Groeidiagram 0-4 jaar jongens NL*. 2010, TNO.
46. TNO, *Groeidiagram 0-4 jaar meisjes NL*. 2010, TNO.

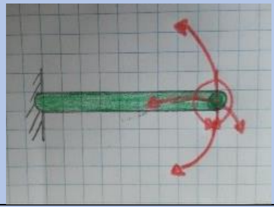
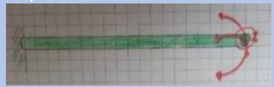
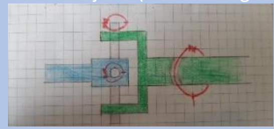
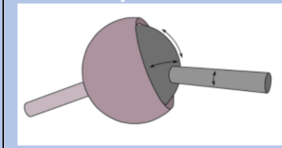
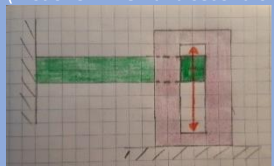
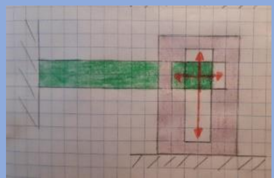
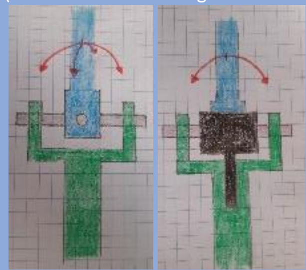
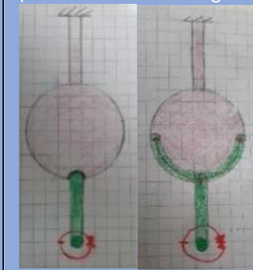
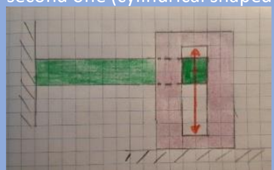
Appendix B

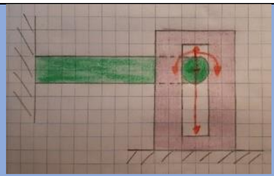
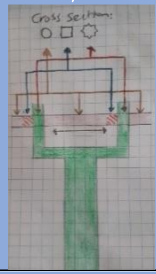
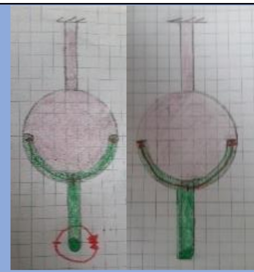
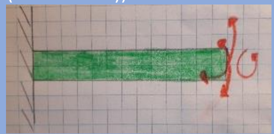
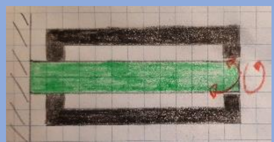
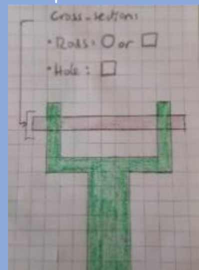
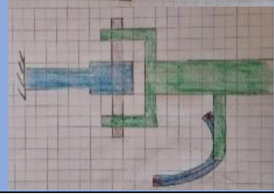
Table with morphologic overview and tables with Harris profiles.

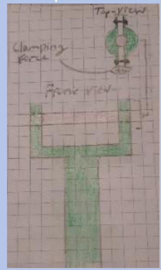
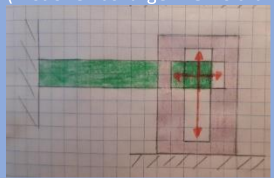
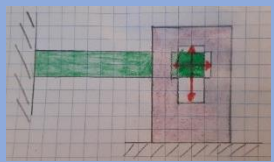
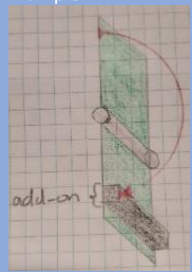
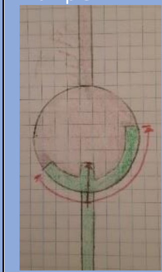
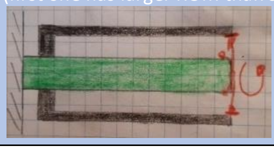
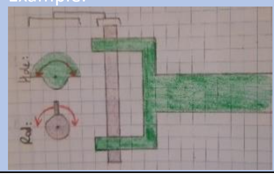
Table 1. Morphologic overview for the design.

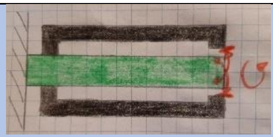
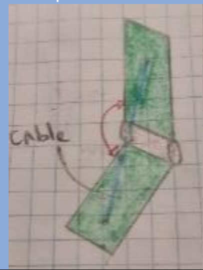
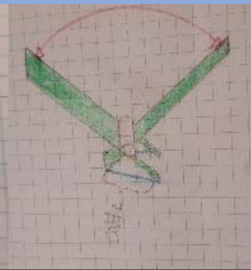
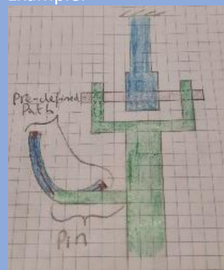
Criteria			**Design options**		
DOF and ROM	0-2 DOF movements	Categories	Compliant hinge	Hinge	Ball joint
		0 DOF	Stiff material	Hinge whose rod has an angular cross-section. 	Ball-socket joint whose rod (connected to the ball) has an angular cross-section and the socket has an angular hole which fits the cross section of the ball's rod perfectly. 
		1 DOF	Flexible material: E.g. Double leaf spring 	Hinge 	Ball-socket joint with one exactly fitting milled out cylindrical hole in the socket in which the rod, attached to the ball and having a cylindrical cross-section, can rotate.  Ball-socket joint with a milled out and one directional path in the socket and a rod, connected to the ball, with an angular shaped cross-section. 
		2 DOF	Flexible material: E.g. Single leaf spring 	Fork joint incl. bearing on shaft 	Saddle joint (+circumduction)

					 
				Universal joint   	joint (+circumduction)  
					Ball-socket joint with a milled out and one directional path in the socket and a rod, connected to the ball, with a cylindrical cross-section. 
					Ball-socket joint with a milled out and two directional path in the socket and a rod, connected to the ball, with an angular shaped cross-section. 

		3 DOF	Rubber-like materials  Rope 	Universal joint (incl. bearings on shaft) 	Ball-socket joint 
	Adjustability of DOF (and stiffness 0 and ∞ Nm/°)		Compliant hinge	Hinge	Ball joint
		Shape lock	A path is milled out in an environmental structure, in such a way that the DOF are limited. Examples: (first one: 1 DOF and second one: 2 DOF)  	Add-on's will prevent rotation in specific directions (limit DOF). The add-on's could be added to the system by the use of screws, magnets or nuts and bolts. Example: (left side: 2 DOF and right side 1 DOF (incl. add-on)) 	A path is milled out in e.g. the socket, in such a way that the required DOF is allowed. Examples: (left side: 1 DOF and right side: 2 DOF)  The socket could be changed (to a socket with other DOF) by the use of screws, magnets, nuts and bolts, glue or Velcro).
			The cross sectional shape limits the amount of DOF. Examples: (first one (angular shaped cross-section): 1 DOF and second one (cylindrical shaped cross-section): 2 DOF) 	Variations in the cross section shape of the rod will cause locking and un-locking of DOF. The largest part of the rod will have a cylindrical cross-section (part of rod without stripes in the example figure) while a small part of the rod has an angular shaped cross section (the striped part in the example figure). When a specific degree of freedom needs to be limited the angular part of the rod slides into the system and locks that degree of freedom. Example: (non-striped part of the rod has a cylindrical cross	Internal rotations of the ball in the socket could be prevented by a rod with an angular-shaped cross-section connected to the ball. Examples: (Left side: circular cross-section 2 DOF and right side: angular cross-section, 1 DOF)

				section, striped part of the rod has an angular cross section) 	
			Add-on’s will prevent rotation in specific directions (limit DOF). The add-on’s could be added to the system by the use of screws, magnets or nuts and bolts. Example: (first one: 3 DOF (without add-on) and second one 2 DOF (incl. add-on))  	The rod with a cylindrical-shaped cross-section can be changed to a rod with an angular-shaped cross-section. This rod with an angular-shaped cross section, allows no DOF around that axis, while the rod with a cylindrical-shaped cross-section allows one DOF around that axis. Example: 	
				A pin is connected to the moving system, this pin moves in a predefined path which restricts the DOF. Example: (first picture: 2 DOF and second picture: 1 DOF (incl. pin and predefined path)  	

		Force lock		The rod is fixed by a squeezing force of screws around the rod which limits the DOF of the system. Example: 	The ball is fixed by bolts which are screwed inside nuts which are fixed onto the socket of the joint and lead the bolts through the socket against the ball. Example: 
	Adjustability of ROM	Categories	Compliant hinge	Hinge	Ball joint
			A path is milled out in an environmental structure in such a way that the ROM is limited. Examples: (first one has larger ROMs than second one)  	Add-ons (shown in example figure) will limit the ROM of the system. These add-on's will be available in various widths. Example:  These add-on's could be attached by the use of screws, magnets or nuts and bolts.	A path is milled out in e.g. the socket, in such a way that the required ROM is allowed. Example:  The socket could be changed (to a socket with other ROM) by the use of screws, magnets or nuts and bolts.
			Add-on's will prevent rotation in specific directions (limit ROM). The add-on's could be added to the system by the use of screws, magnets or nuts and bolts. Example: (first one has larger ROM than second one) 	The rod has an extra pin perpendicular on it, therefore the shape of the hole can decide the system's ROM as shown in the figure. Example: 	Holes with screw thread are milled into the ball. Screws (black in the example figure) can be rotated in them. With these screws the ROM can be defined. Example 

			 These add-on’s could be attached by the use of screws, magnets or nuts and bolts.		
				A cable can be used on the inside (first example figure) or outside (second example figure) of the system to limit the ROM. In this way the ROM is adjustable by lengthening or shortening of the cable. Examples:  	
				A pin is connected to the system, this pin moves in a predefined path which restricts the ROM. Example:  	

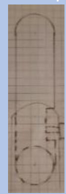
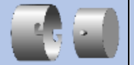
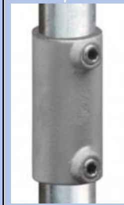
Demountable connection system	Fixating all translations and rotations (fixation and un-fixation of two systems possible (torso and joint or limb and joint)	Categories	Shape lock								Force lock		
			Click system Example: 	Hook system Example: 	Velcro (for longitudinal movements) Example: 	Flattened axis with socket set screw Example: 	Screw thread coupling (inside and outside) Example: 	Nuts and bolts coupling Example: 	Tubes with ball spring plunger Example: 	Bayonet Mount Example: 	Pipe coupling Example: 	Clamping force coupling Example: 	Elastic cable Example: 

Table 2. Harris profile Hinge concepts: 0-2 DOF.

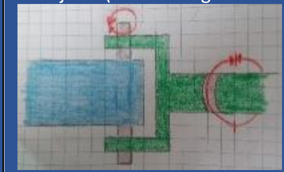
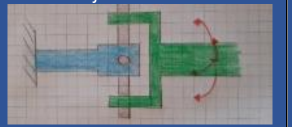
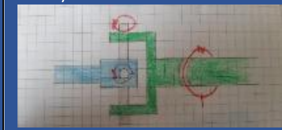
	0-2 DOF	Fork joint (incl bearing on shaft) 	Universal joint 	Universal joint (incl bearing on shaft) 	Explanation
Mechanical requirements	Allows 0-2 DOF movements	-	++	++	All three systems allow 0-2 DOF, but the fork joint (incl. bearing on shaft) is based on a rotation, which is not similar to human body: • To fully allow 2 DOF, a fork joint requires to be able to make full rotations, which can lead to a wrong orientation of the under arm, lower leg, hand or foot. • A dead point is present when the fork joint is fully stretched. At this position 'sideways' movements first require a rotation.
	Adjustability of DOF	++	++	++	
	Adjustability of ROM within range	++	++	++	
Geometric requirements	Fixation of translations and rotations	NA	NA	NA	
	Add ability of demountable system	++	++	++	
	Diameter smaller than 2.6 cm	++	++	++	
General requirements	Modular and adjustable	++	++	++	
	Safe and robust	++	++	++	
	No limited shelf life	++	++	++	
	Easy to handle	++	++	++	
	Partly re-useable	++	++	++	
	Maintainable and repairable	++	++	++	

Table 3. Harris profile of concepts of adjustability of DOF and stiffness

	Adjustability of DOF	Add-ons	Variations in cross section shape	Change of rod (cylindrical to angular shaped cross section)	Pin	Squeezing	Explanation
Mechanical requirements	Allows 0-2 DOF movements	NA	NA	NA	NA	NA.	
	Adjustability of DOF and stiffness	++	++	++	++	++	
	Adjustability of ROM within range	NA	NA	NA	NA	NA	
Geometric requirements	Fixation of translations and rotations	NA	NA	NA	NA	NA	
	Add ability of demountable system	NA	NA	NA	NA	NA	
	Diameter smaller than 2.6 cm	++	++	++	++	++	
General requirements	Modular and adjustable	++	++	++	++	++	
	Safe and robust	+	+	++	++	+	A pin and different rods are both most robust concepts, because they can handle large forces, while the other three systems are a bit less robust.
	No limited shelf life	++	++	++	++	++	
	Easy to handle	+	+	+	++	+	A pin is most easy in use to prevent movements in certain directions. The other concepts need to be set up in a certain way, while the pin only needs to be inserted.
	Partly re-useable	++	++	++	++	++	
	Maintainable and repairable	++	++	++	++	++	

Table 4. Harris profile concepts of adjustability of ROM

	Adjustability of ROM	Add-ons	Rod with pin	Cable	Pin with pre-defined path	Explanation
Mechanical requirements	Allows 0-2 DOF movements	NA	NA	NA	NA	
	Adjustability of DOF and stiffness	NA	NA	NA	NA	
	Adjustability of ROM within range	++	++	++	+	All concepts could adjust the ROM within the range of 0-3 year old infants. However the pin with pre-defined path is limited due to limited path possibilities because of the fact that the path needs to be attached to the system in a certain way. The other three concepts seem to be better suitable.
Geometric requirements	Fixation of translations and rotations	NA	NA	NA	NA	
	Add ability of demountable system	NA	NA	NA	NA	
	Diameter smaller than 2.6 cm	-	++	-	--	The add-ons and cable concepts both require more space than a rod with pin. The pin with predefined path even more.
General requirements	Modular and adjustable	++	++	++	++	
	Safe and robust	++	++	+	++	The add-ons, the rod with pin and the pin with predefined path are three concepts which are most robust, the cable could namely get tangled up.
	No limited shelf life	+	+	+	+	
	Easy to handle	++	++	++	++	
	Partly re-useable	++	++	++	++	
	Maintainable and repairable	++	++	++	++	

Table 5. Harris profile of concepts of demountable connection system.

	Demountable connection system	Click system	Hook system	Velcro	Flattened axis with socket set screw	Screw thread	Nuts and bolts coupling	Tubes with ball	Bayonet Mount	Pipe coupling	Clamping force coupling	Elastic cable	Explanation
Mechanical requirements	Allows 0-2 DOF movements	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
	Adjustability of DOF and stiffness	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
	Adjustability of ROM within range	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
Geometric requirements	Fixation of translations and rotations	++	+	+	++	++	++	++	++	++	+	+	
	Add ability of demountable system	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	
	Diameter smaller than 2.6 cm	++	++	++	++	++	++	++	++	++	++	++	
General requirements	Modular and adjustable	-	-	++	++	-	++	-	-	++	++	++	All concepts are modular and adjustable. The click system, hook system, screw thread, tubes with ball and bayonet mount are not very easy adjustable. They need to be build again with another design, when another configuration is needed.
	Safe and robust	++	-	-	++	++	++	+	+	+	+	-	All concepts are safe and robust, except for the hook system, Velcro and elastic cable, which can loosen or wear out during shaking. The most robust systems are the click system, the flattened axis with socket set screw, screw thread and nuts and nuts and bolts coupling because they could not loosen during shaking.
	No limited shelf life	++	++	++	++	++	++	++	++	++	++	++	
	Easy to handle	++	++	++	++	+	++	++	++	++	++	++	All concepts are easy to handle. But the screw thread coupling is a bit more difficult to handle due to alignment problems.
	Partly re-useable	++	++	++	++	++	++	++	++	++	++	++	
	Maintainable and repairable	++	++	++	++	++	++	++	++	++	++	++	

Appendix C

Information sheet and consent Form for indicative mechanical shaking test.

Informatie blad indicatieve schudtest (30-05-2021)

Doel van het onderzoek: Uitzoeken of en tot welke geteste leeftijd (hangt samen met zowel het gewicht als de afstand tot het 'center of mass') het (vereenvoudigde) ontwerp heel blijft tijdens het schudden. Er worden twee ontwerpen getest: de aluminium en de 3D geprinte variant.

Handeling die je moet uitvoeren:
10x per instelling van gewicht en afstand moet er een zo hard mogelijke schudbeweging worden gemaakt.

Je kunt altijd stoppen met meewerken aan dit onderzoek.

Enkel je gewicht en lengte zal worden gebruikt voor dit onderzoek. Ook zal het experiment opgenomen worden met een videocamera. Deze informatie wordt enkel voor het onderzoek gebruikt.

Voor meer vragen over dit onderzoek zijn hier contactgegevens:

Eva Blom
evablom2017@gmail.com
0613703647

Consent Form for [*Shaking experiment*]

Please tick the appropriate boxes	Yes	No
Taking part in the study		
I have read and understood the study information dated [30/05/2021], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	O	O
I consent voluntarily to be a participant in this study and understand that I can withdraw from the study at any time, without having to give a reason.	O	O
I understand that taking part in the study involves being recorded on video.	O	O
Use of the information in the study		
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	O	O

Signatures

______________________ ______________________ ________

Name of participant

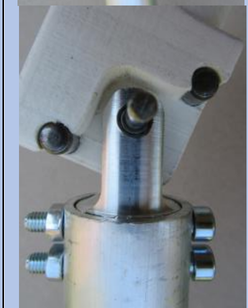
______________________ ______________________ ________

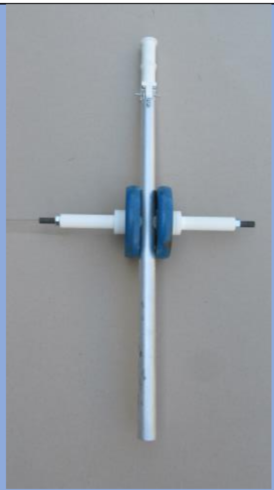
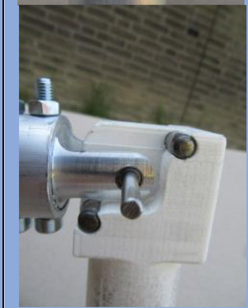
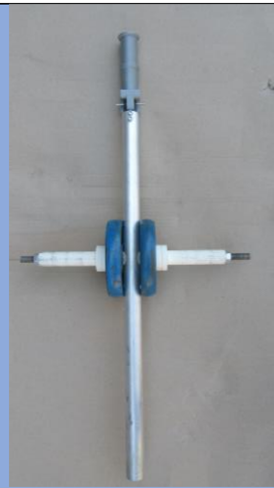
Researcher name

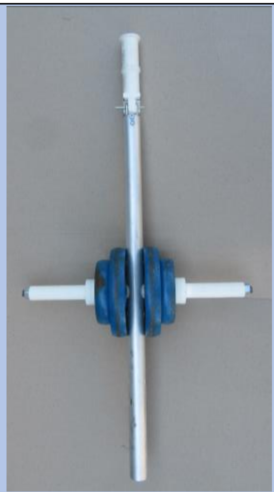
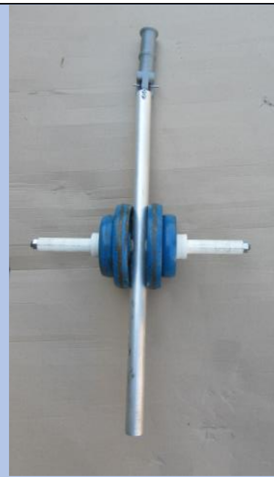
Study contact details for further information:
Eva Blom
0613703647
evablom2017@gmail.com

Appendix D

Table with photo’s made of the two yokes after each of the shaking tests.

Age (months)	Mass (kg) (male)	Distance to centre of mass (cm)	Aluminium yoke				Carbon fibre filled nylon 3D printed yoke			
			Mass of weights	Setup (front view)	Visible damage aluminium yoke	After picture of yoke (front and side views)	Mass of weights	Setup (front view)	Visible damage Nylon yoke	After picture of yoke (front and side views)
Before pictures						 				 

1	4.3	28.0	4530 g		A small black stripe visible on the yoke	 	4.3 kg		Yoke a bit dented at place of impact	 

6	7.6	32.8	7700 g		Black stripe, a small dent on the yoke	 	8000 g		yoke a bit dented	  

12	10.3	36.7	10850 g		Black stripe, a small dent on the yoke	 	10810 g		yoke dented	  

24	13.0	48.1	13850 g		Black stripe, a small dent on the yoke	 	14080		yoke dented	  

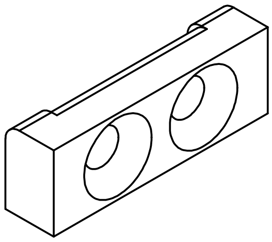
36	15.3	51.7	16110g		Black stripe, a small dent on the yoke.	 	15560g		yoke dented	  

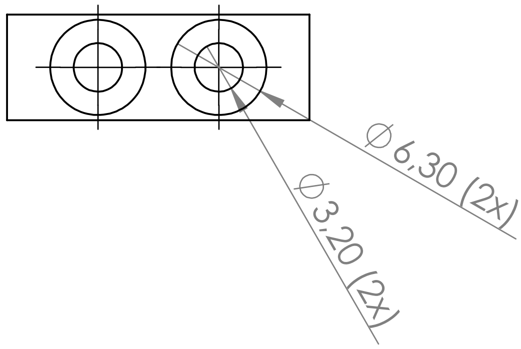
After last extra shake test										yoke dented	

Appendix E

All technical drawings of the prototype are added in this appendix:

E.1. Technical drawings of post-processing steps of 3D printed parts (PLA)
E.2. Technical drawings of aluminium parts to be made
E.3. Technical drawings of post-processing steps of 3D printed parts (carbon fibre filled nylon)
E.4. Technical drawings of post-processing steps of stainless steel laser cut parts
E.5. Technical drawings of stainless steel parts to be made
E.6. List of parts to be bought





Nabewerkingen op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Elleboog, knie begrenzing extension (x1)

MATERIAL: PLA

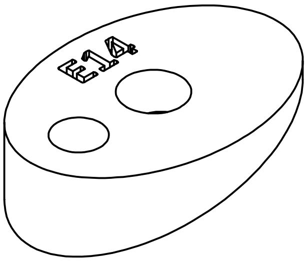
DWG NO.

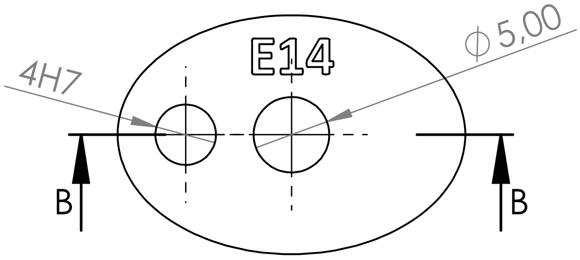
A4

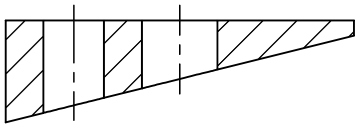
WEIGHT:

SCALE:2:1

SHEET 1 OF 20



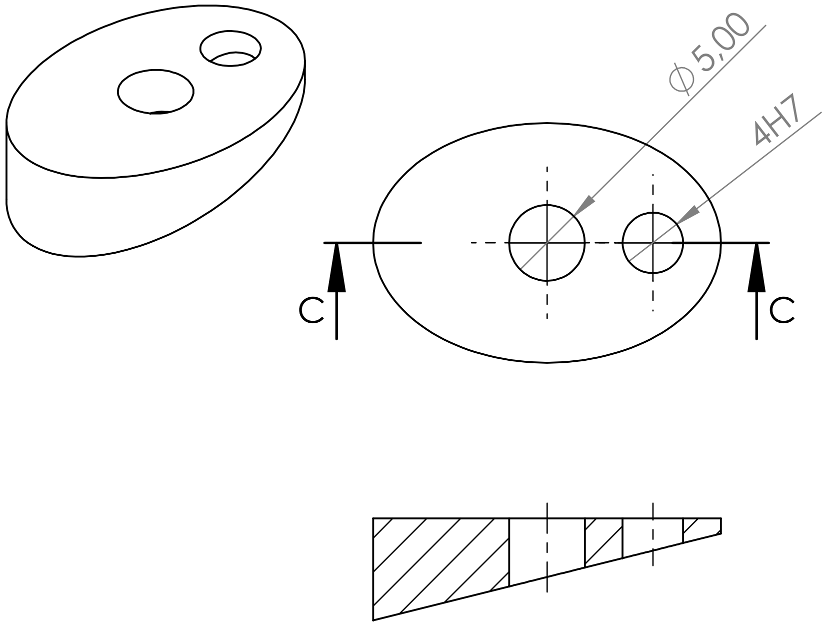




SECTION B-B

Nabewerking op basis van 3D geprint onderdeel

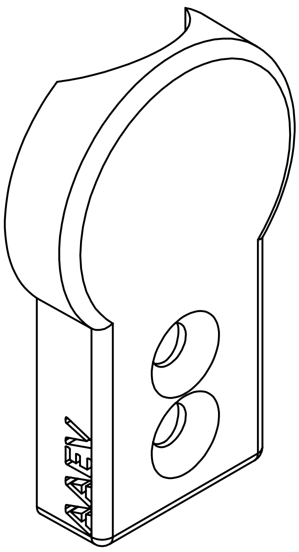
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE: Elleboog opzetstuk 14 graden (1x)	
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: PLA	DWG NO.	A4
			WEIGHT:	SCALE:2:1	SHEET 2 OF 20

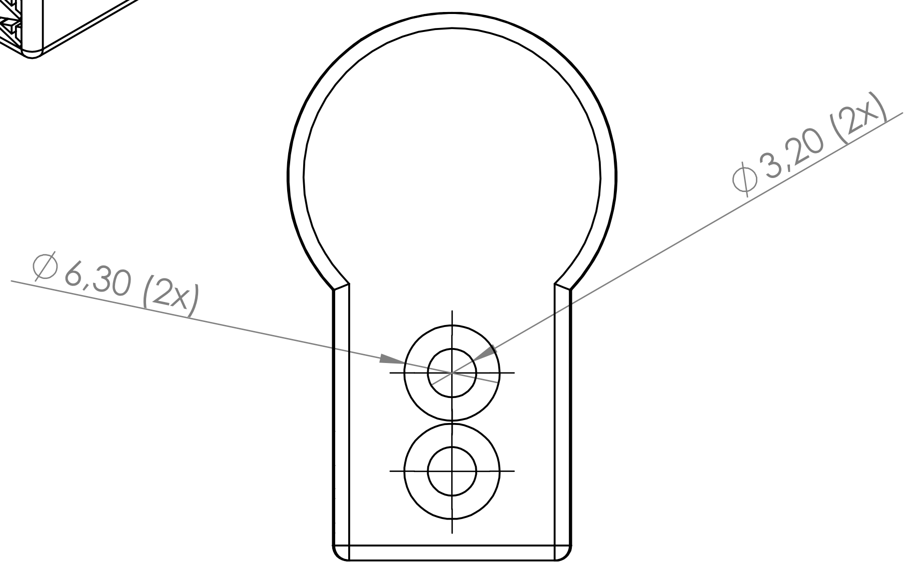


SECTION C-C

Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE: Elleboog opzetstuk 14 graden tegengesteld (1x)	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: PLA	DWG NO.	A4
				WEIGHT:	SCALE:2:1	SHEET 3 OF 20





Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: **Enkel begrenzing max eversion (1x)**

MATERIAL: PLA

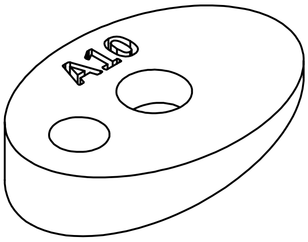
DWG NO.

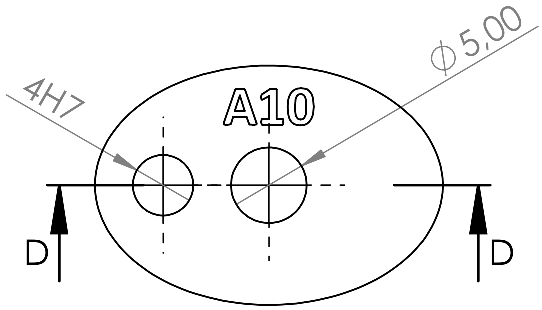
A4

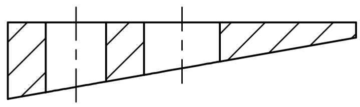
WEIGHT:

SCALE:2:1

SHEET 4 OF 20



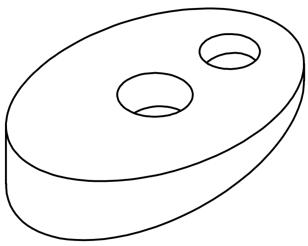


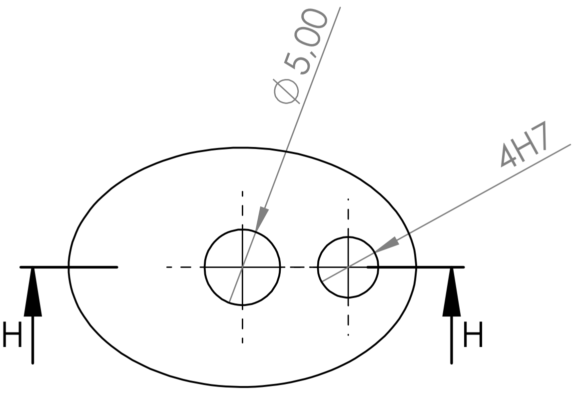


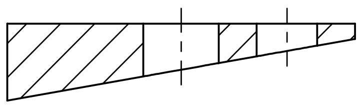
SECTION D-D

Nabewerking op basis van 3D geprinte onderdelen

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE: Enkel opzetstuk 10 graden (1x)	
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: PLA	DWG NO.	A4
			WEIGHT:	SCALE:2:1	SHEET 5 OF 20







SECTION H-H

Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE: Enkel opzetstuk 10 graden tegengesteld (1x)

MATERIAL: PLA

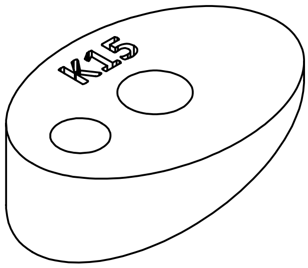
DWG NO.

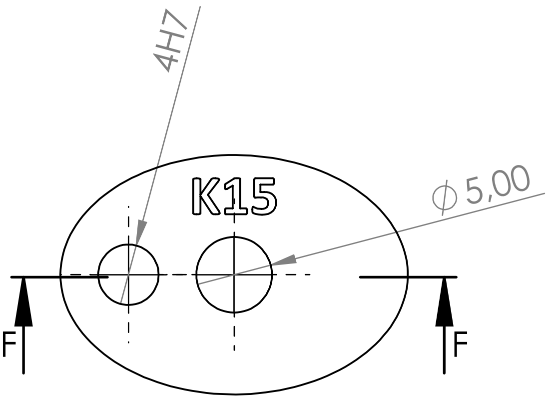
A4

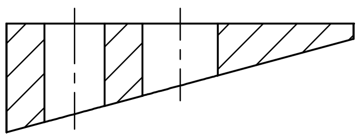
WEIGHT:

SCALE:2:1

SHEET 6 OF 20







SECTION F-F

Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: **Knie opzetstuk 15 graden (1x)**

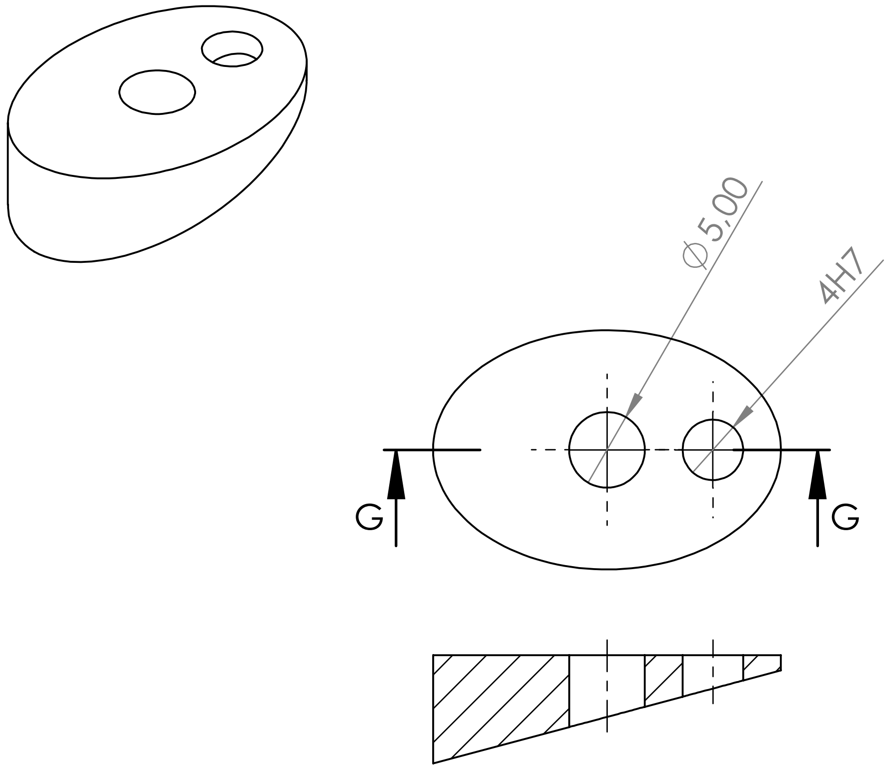
MATERIAL: PLA

DWG NO. — A4

WEIGHT:

SCALE:2:1

SHEET 7 OF 20



SECTION G-G

Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: PLA

WEIGHT:

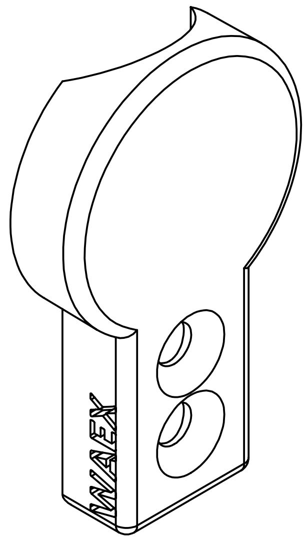
TITLE: Knie opzetstuk 15 graden tegengesteld (1x)

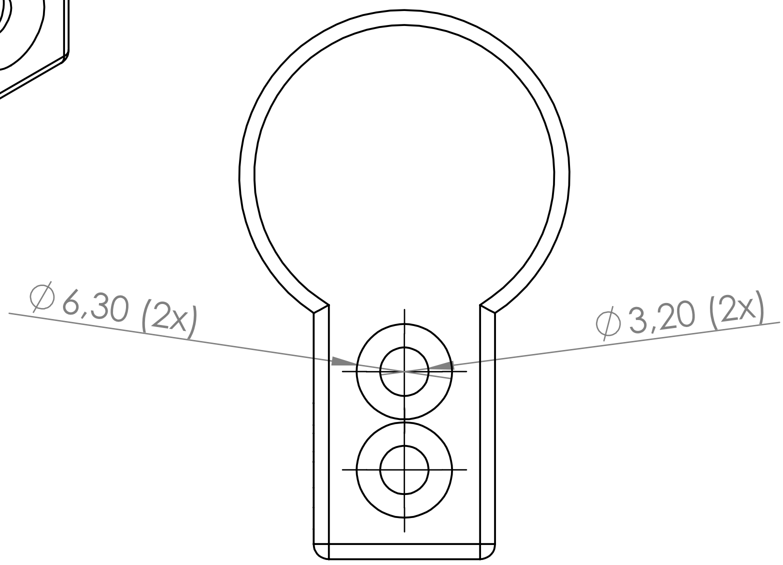
DWG NO.

A4

SCALE:2:1

SHEET 8 OF 20





Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Pols begrenzing max extension (1x)

MATERIAL: PLA

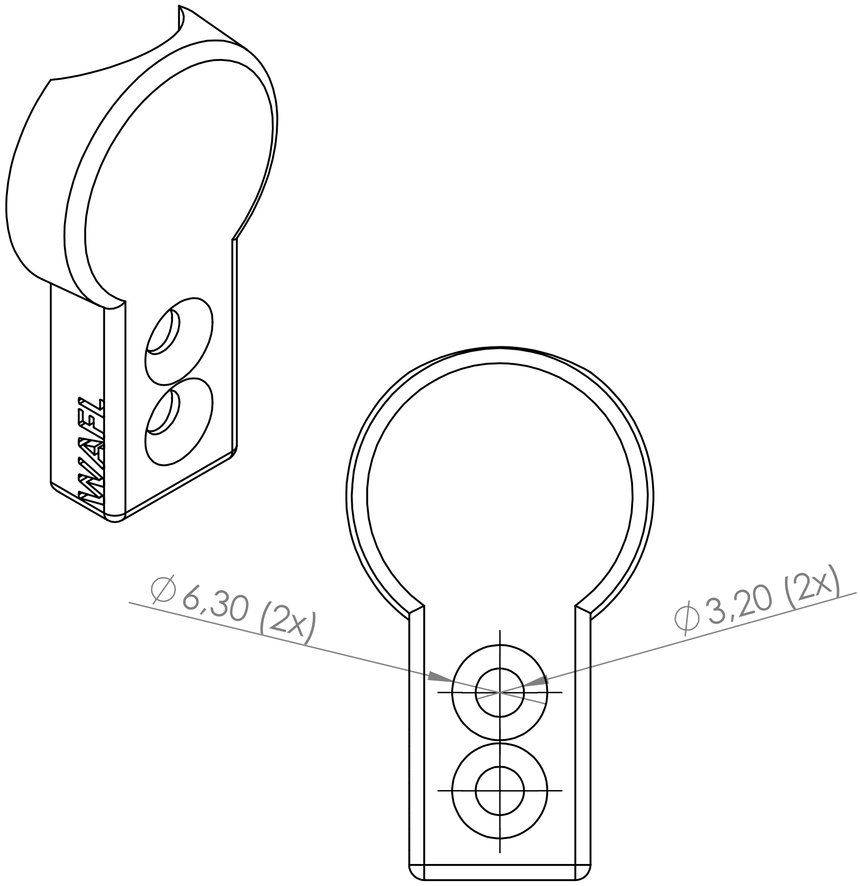
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 9 OF 20



Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Pols begrenzing max flexion

MATERIAL: PLA

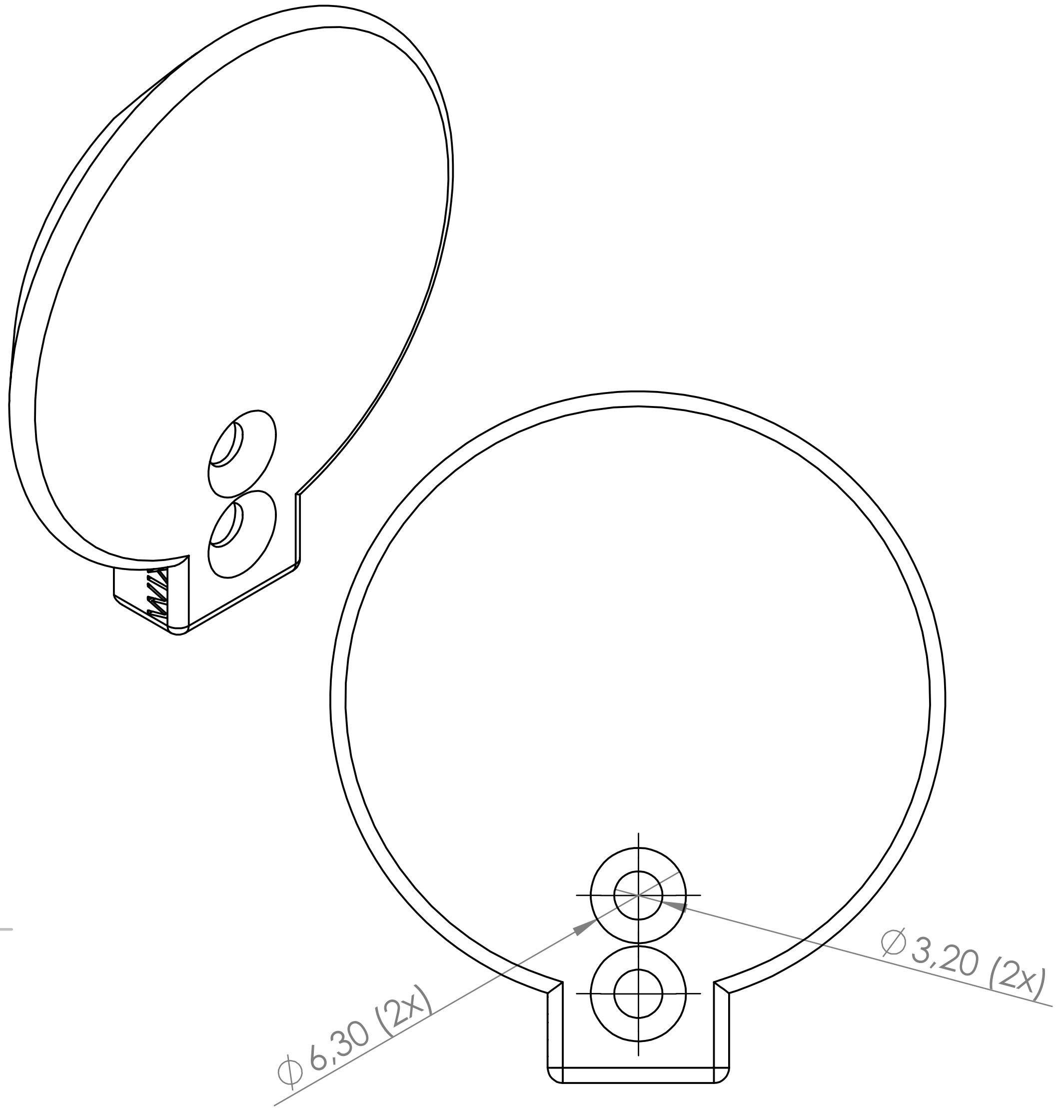
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 10 OF 20



Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING · REVISION

	NAME	SIGNATURE	DATE	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				

TITLE: Pols begrenzing min extension (1x)

MATERIAL: PLA

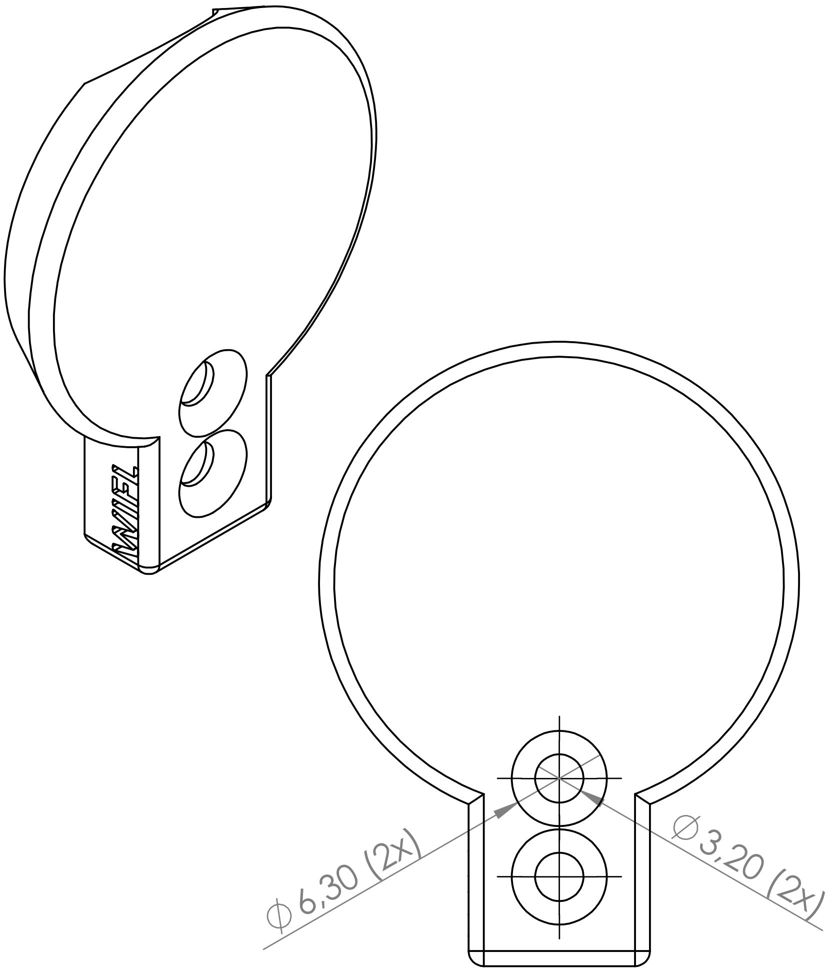
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 11 OF 20



Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE: Pols begrenzing min flexion (1x)

MATERIAL: PLA

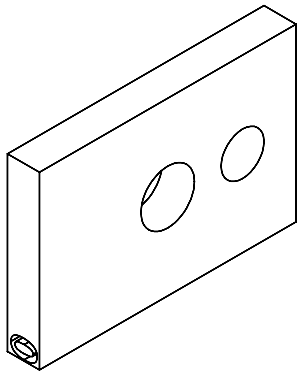
DWG NO.

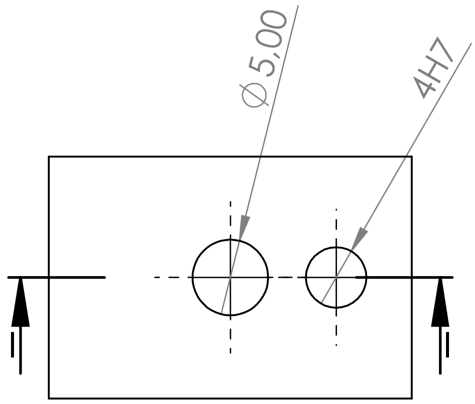
A4

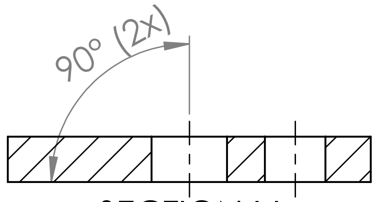
WEIGHT:

SCALE:2:1

SHEET 12 OF 20







SECTION I-I

Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

Representatie lichaam 0 graden (3x)

MATERIAL: PLA

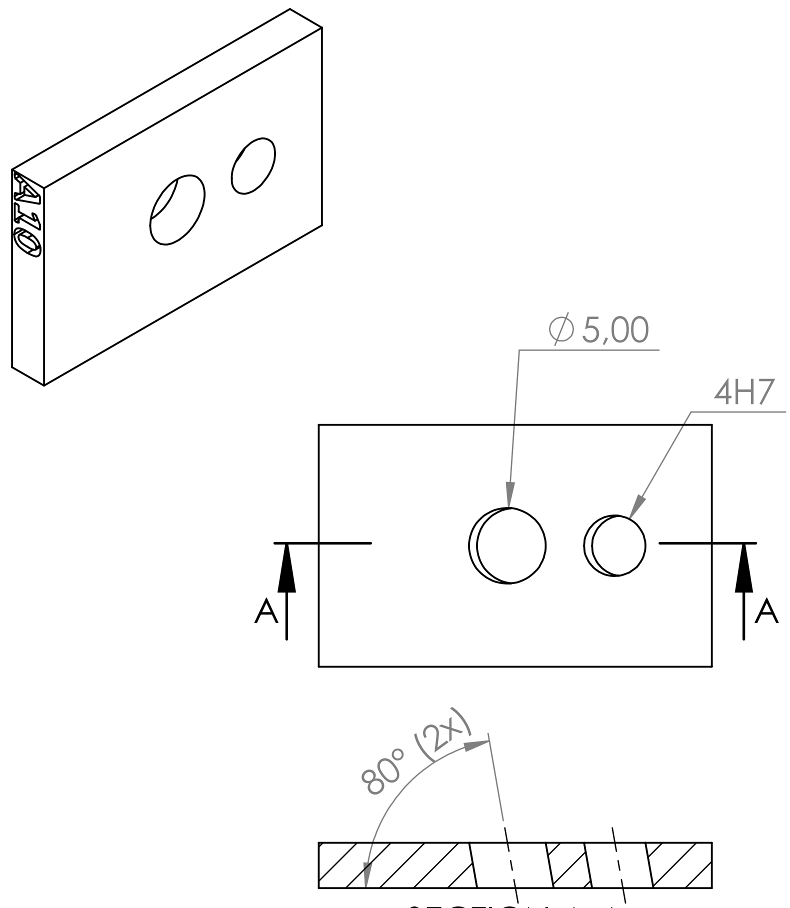
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 13 OF 20



SECTION A-A

Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE: Representatie lichaam 10 graden (1x)

MATERIAL: PLA

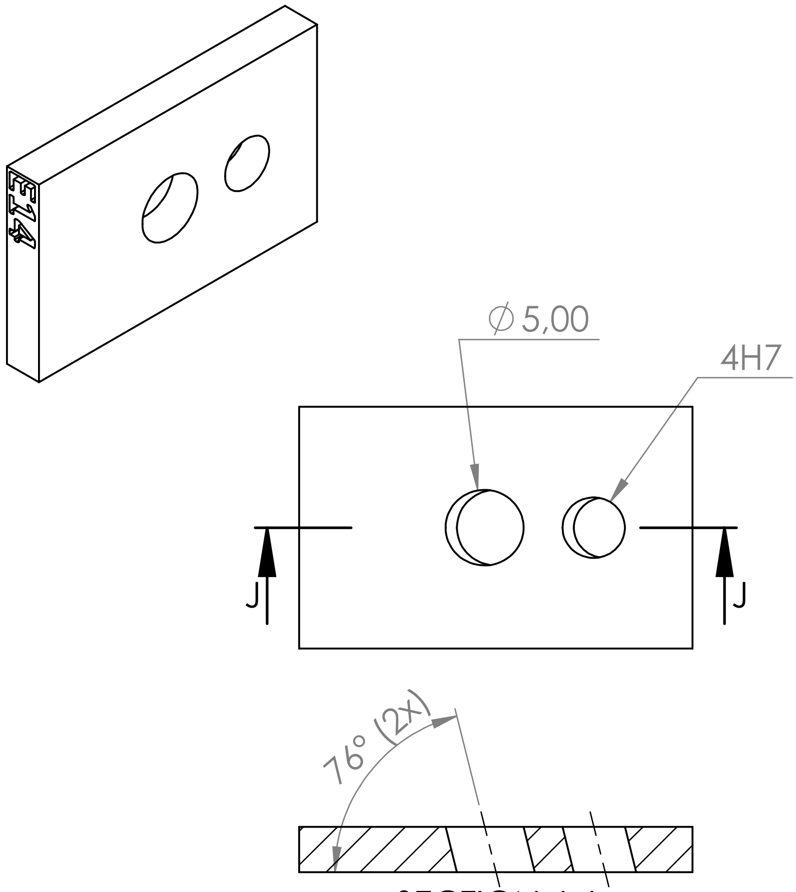
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 14 OF 20



SECTION J-J

Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

Representatie lichaam 14 graden

MATERIAL: PLA

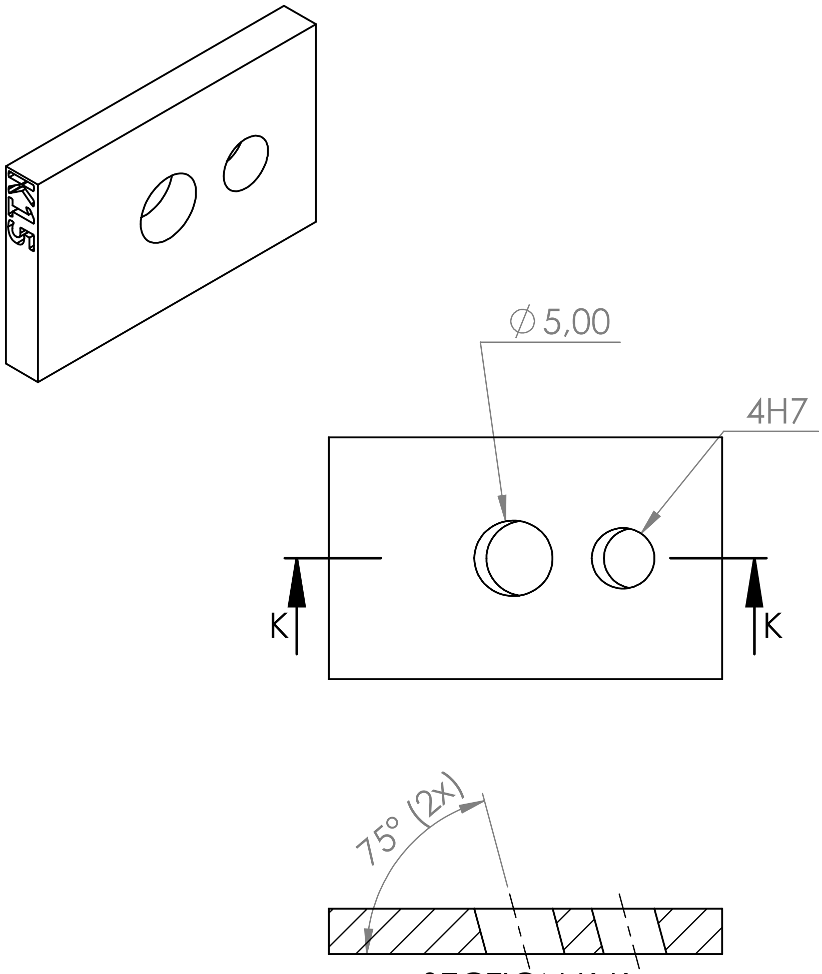
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 15 OF 20



SECTION K-K

Nabewerking op basis van 3D geprinte onderdelen

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:
Representatie lichaam
15 graden

MATERIAL:
PLA

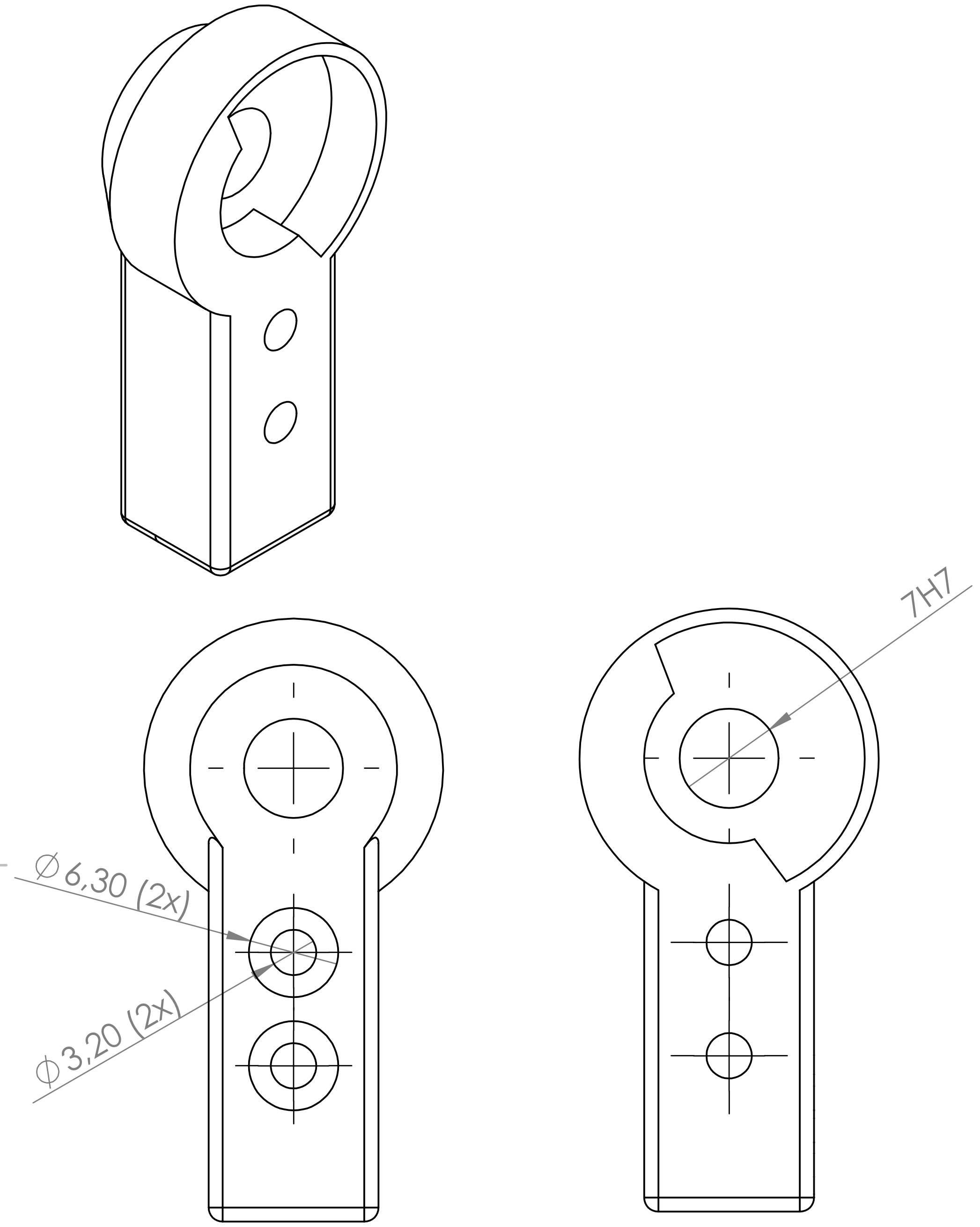
DWG NO.

A4

WEIGHT:

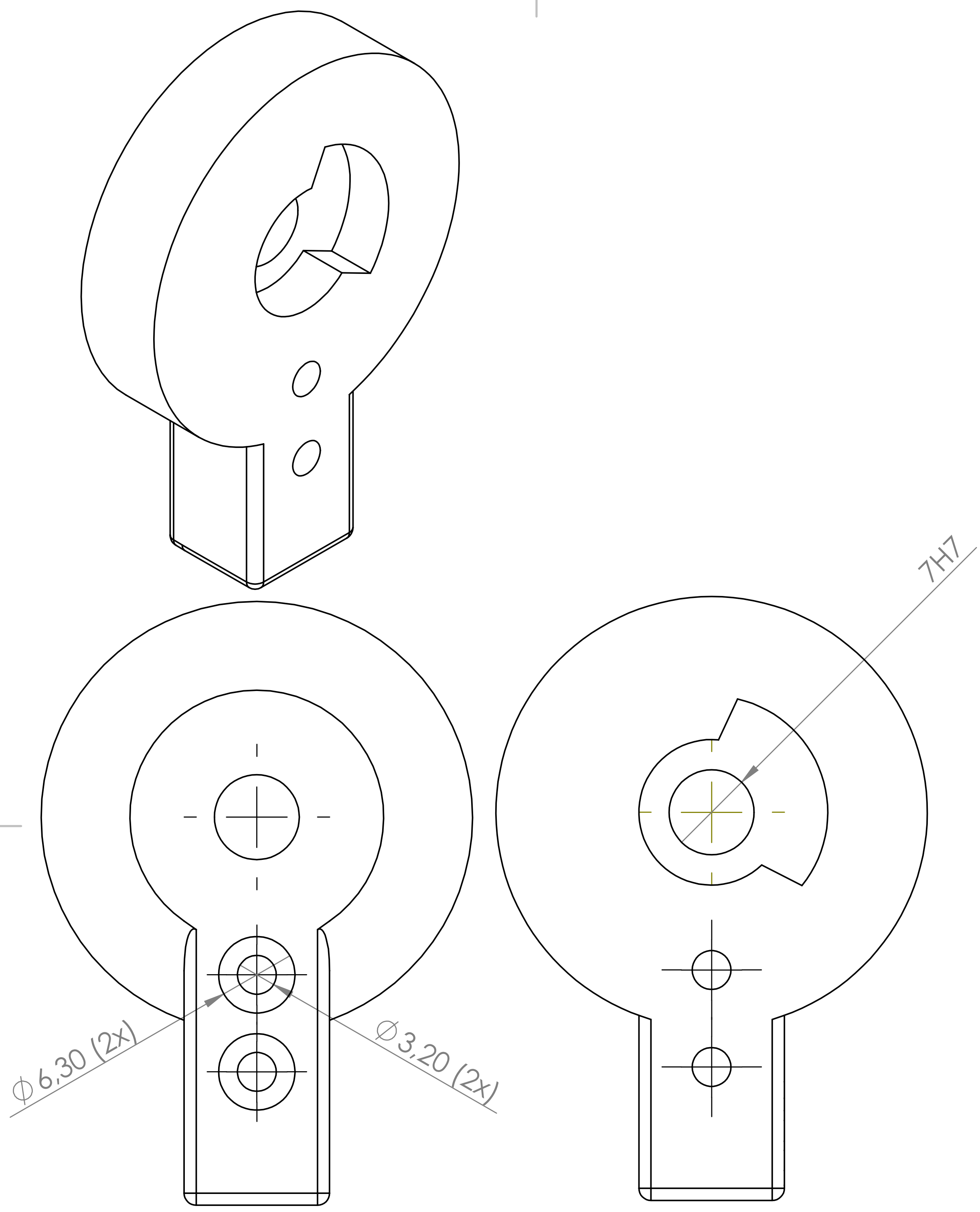
SCALE:2:1

SHEET 16 OF 20



Nabewerkingen op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE: Heup begrenzing max adduction, flexion, extension (1x)	
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: PLA	DWG NO.	A4
			WEIGHT:	SCALE:2:1	SHEET 17 OF 20



Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING
			REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Heup begrenzing min adduction, flexion, extension (1x)

MATERIAL: PLA

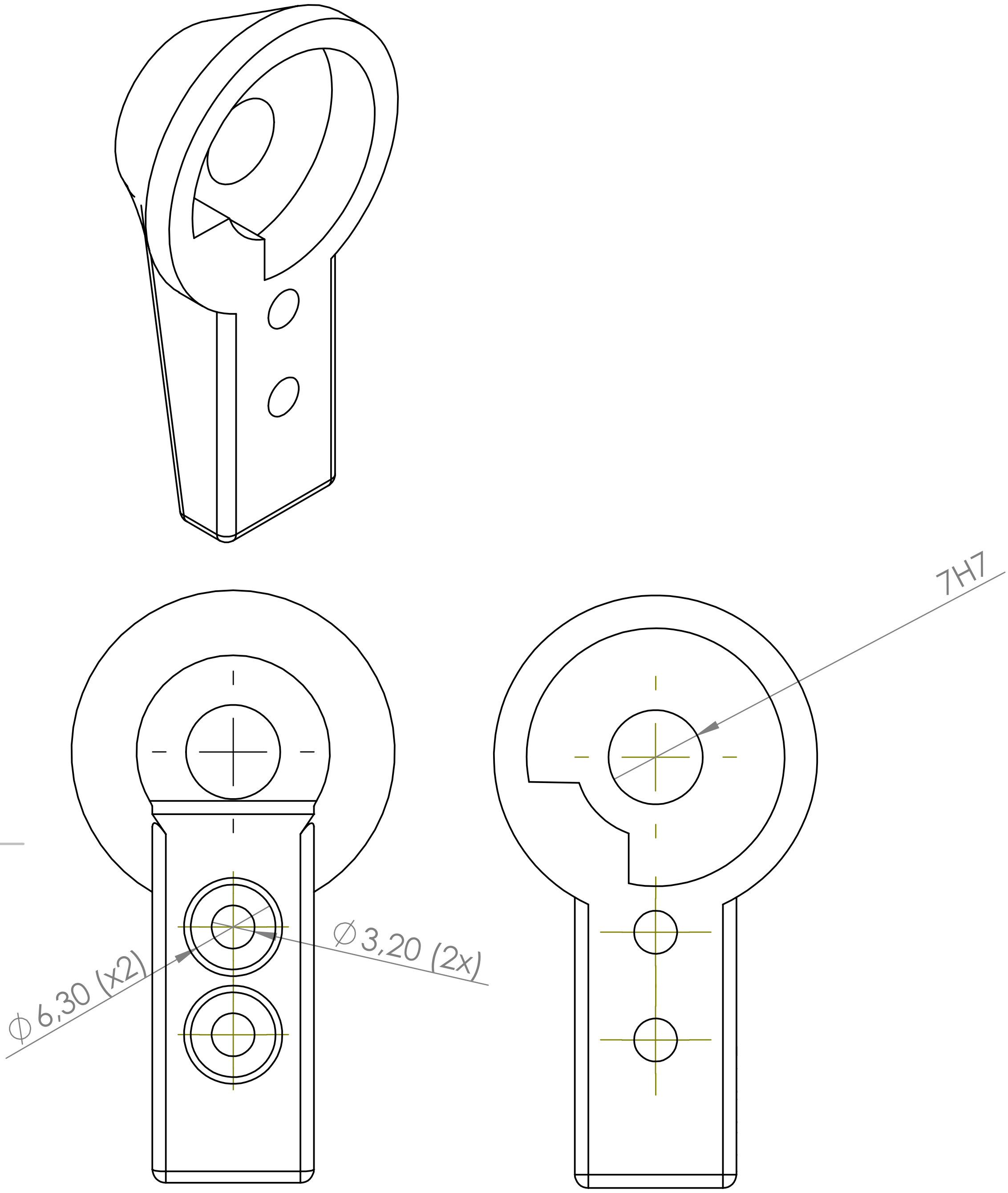
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 18 OF 20



Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Schouder begrenzing max adduction, flexion, extension (1x)

MATERIAL: PLA

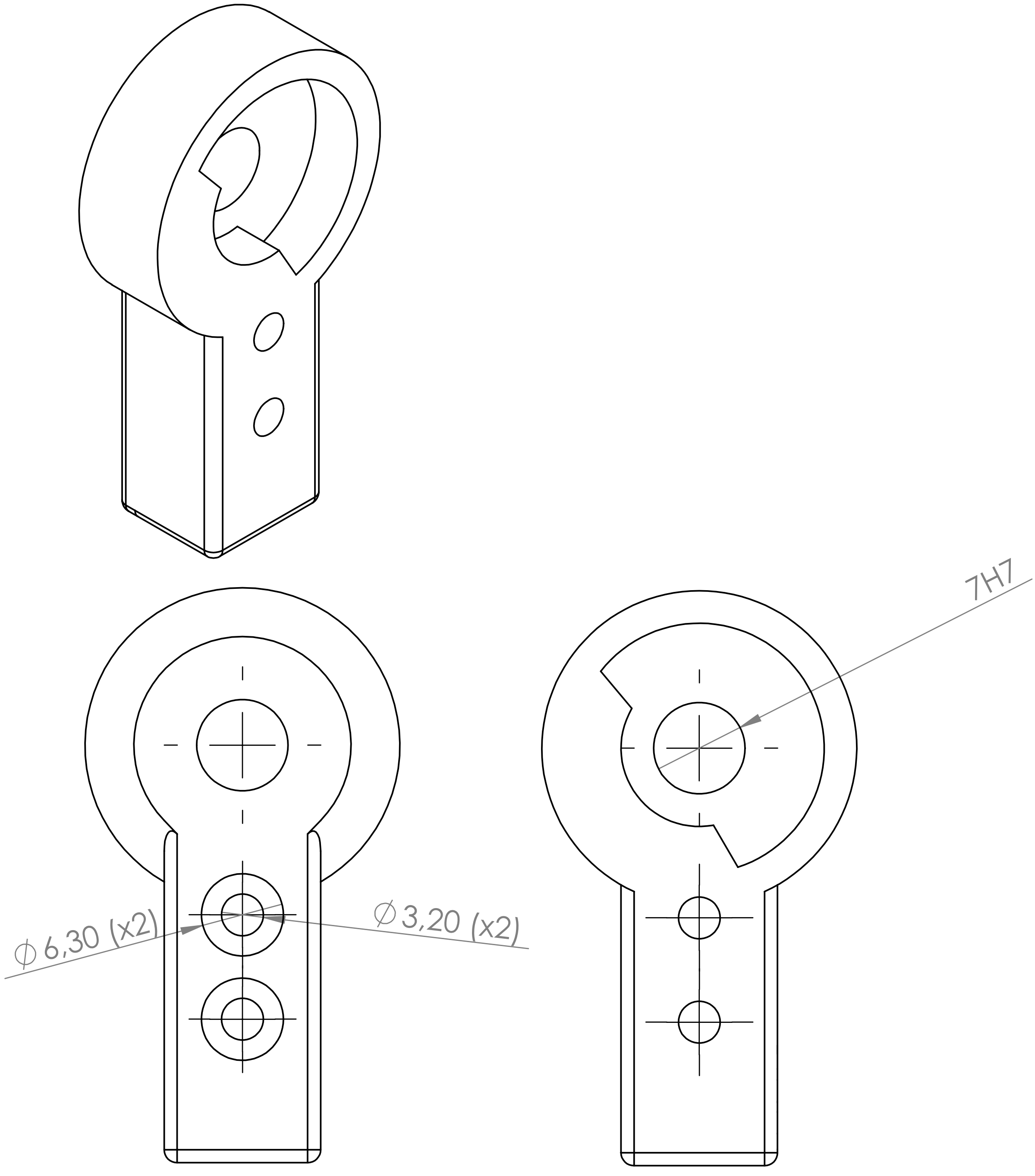
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 19 OF 20



Nabewerking op basis van 3D geprint onderdeel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A				MATERIAL: PLA	
				WEIGHT:	

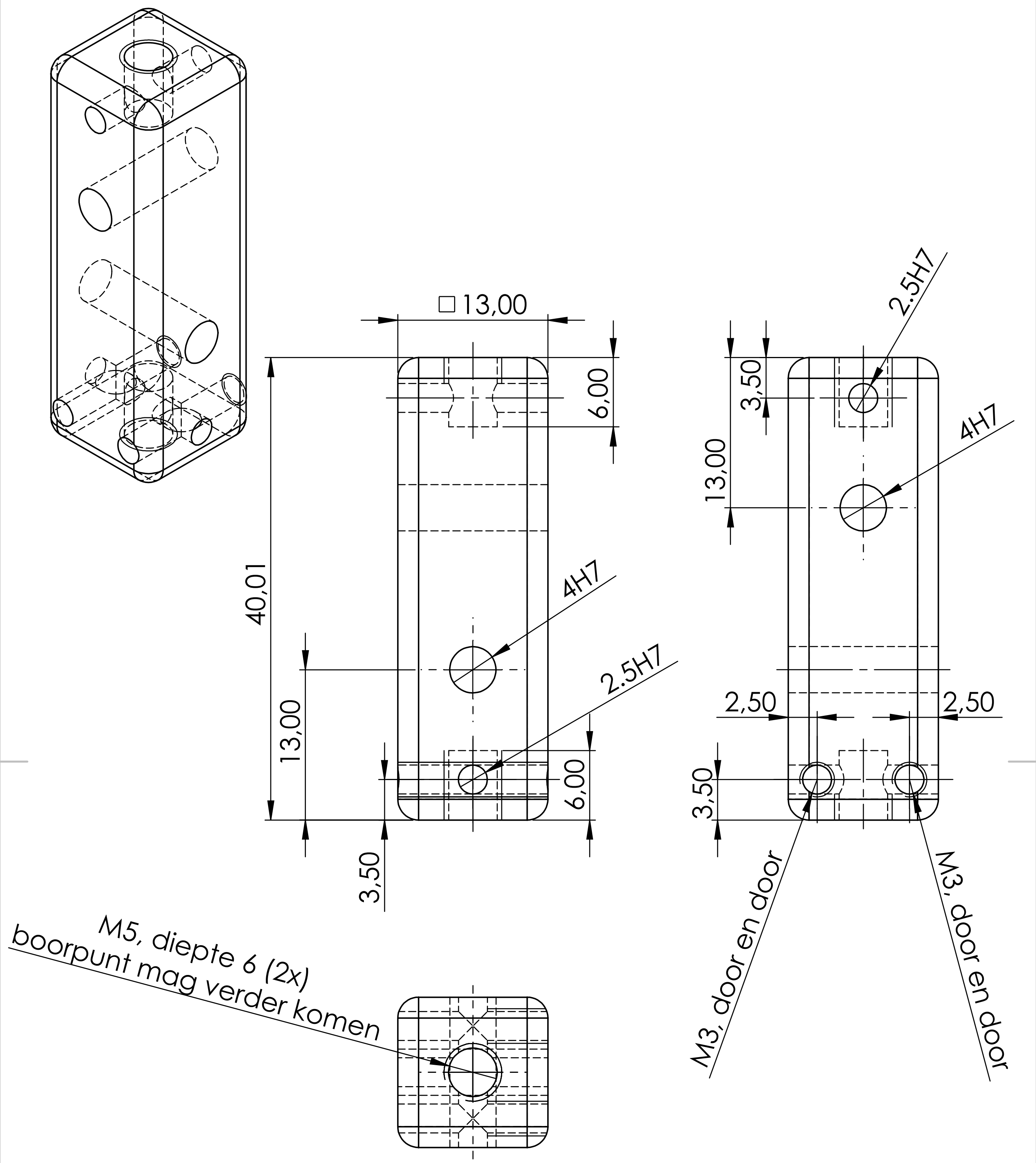
TITLE: Schouder begrenzing min adduction, flexion, extension (1x)

DWG NO.

A4

SCALE:2:1

SHEET 20 OF 20



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:
Kruis blok enkel, pols, knie, elleboog (1x)

MATERIAL:
Aluminium

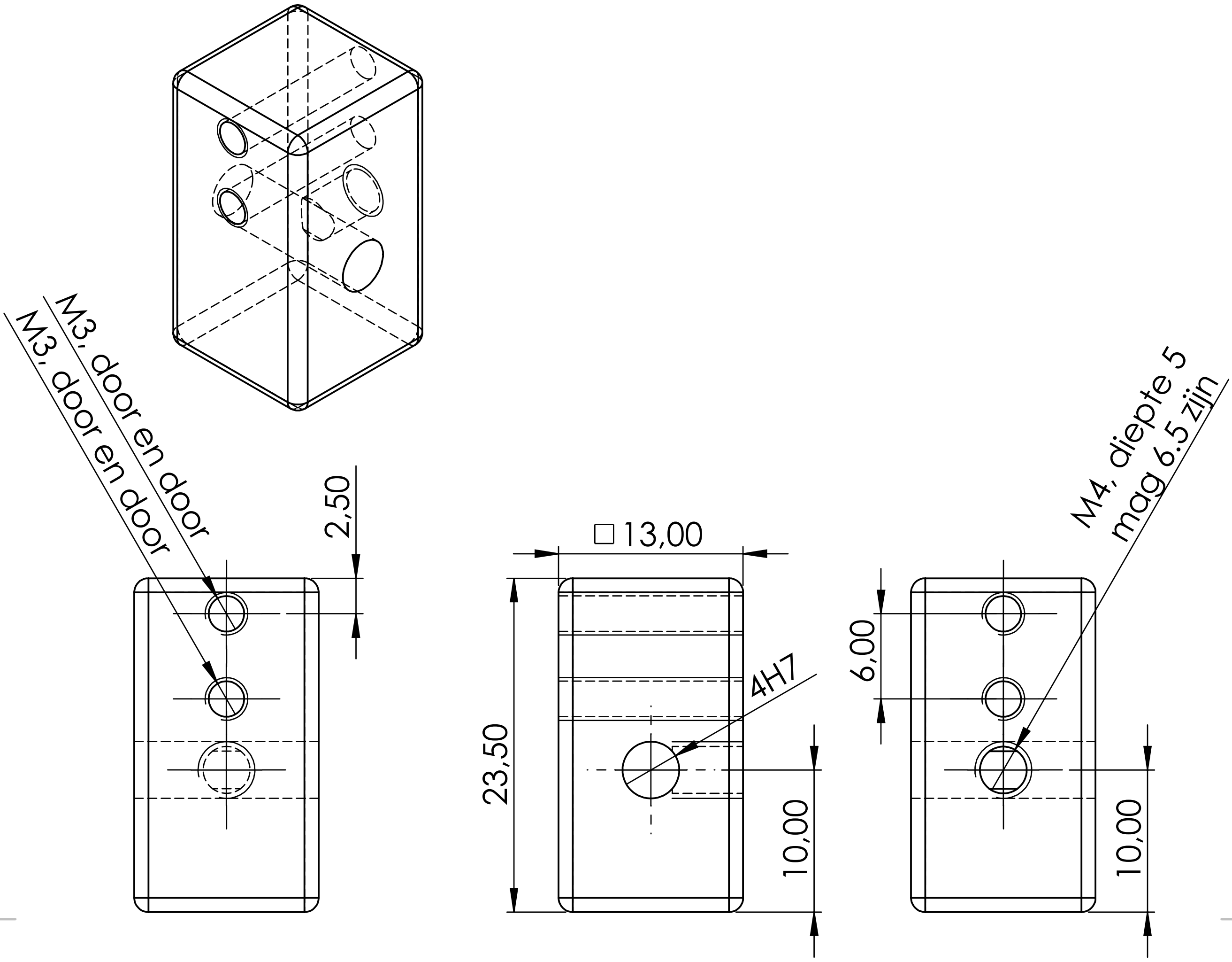
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Kruis heup en schouder (1x)

MATERIAL: Aluminium

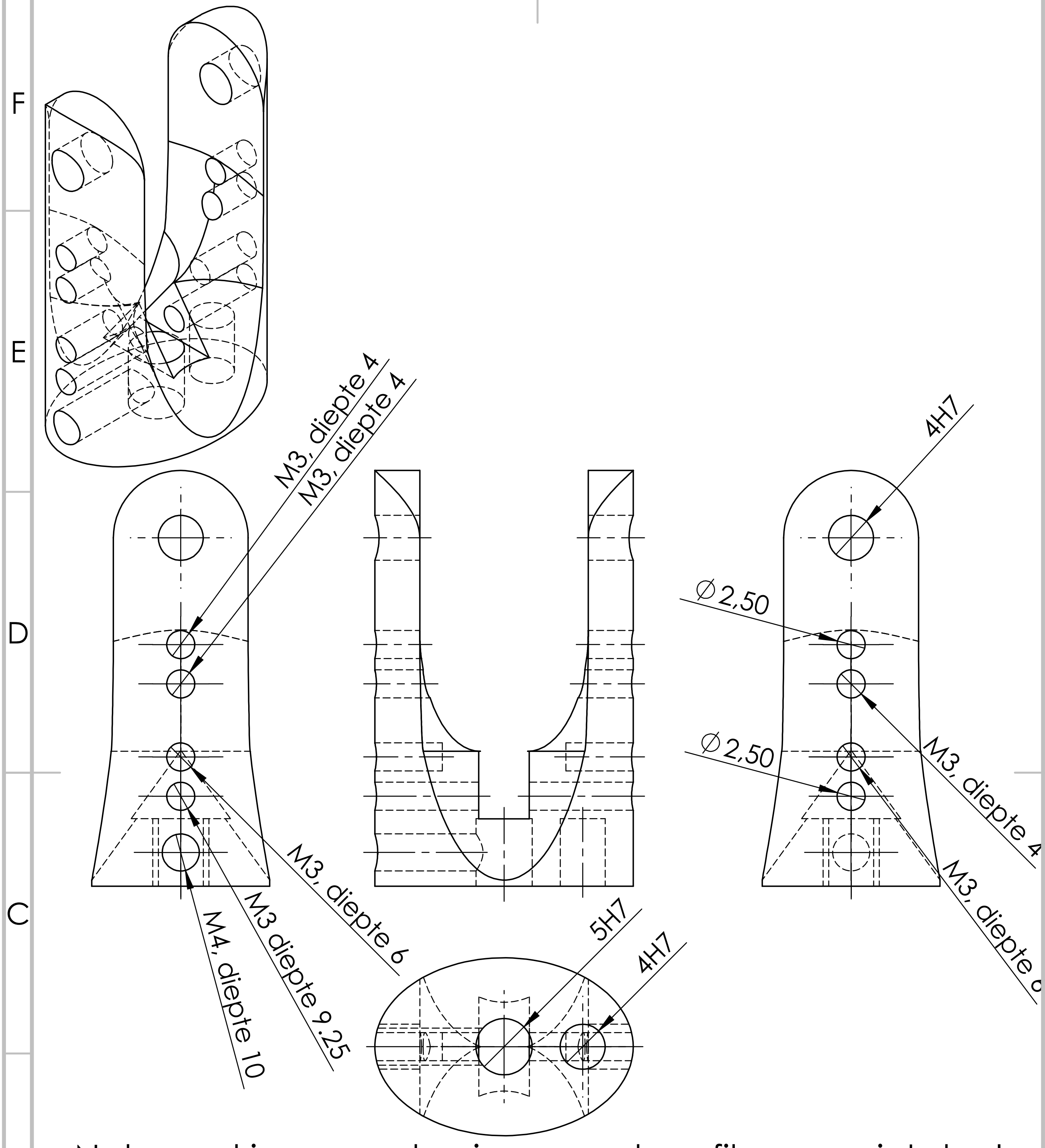
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 2 OF 2



Nabewerkingen op basis van carbon fibre geprint deel

Let op, de schroefdraden konden niet worden aangegeven op de tekening aangezien ze niet in het 3d print model mogen staan

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Klauw (4x)

MATERIAL:
Carbon Fibre 3D printed
ONYX PA12

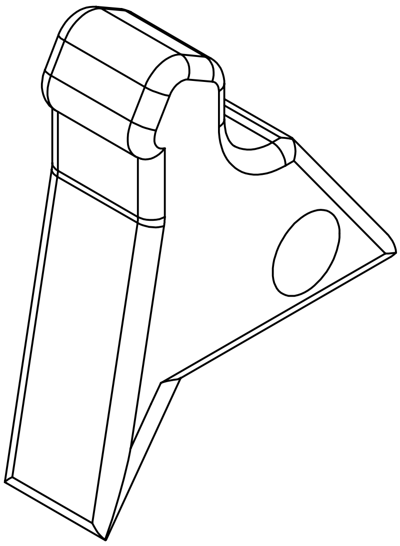
DWG NO.

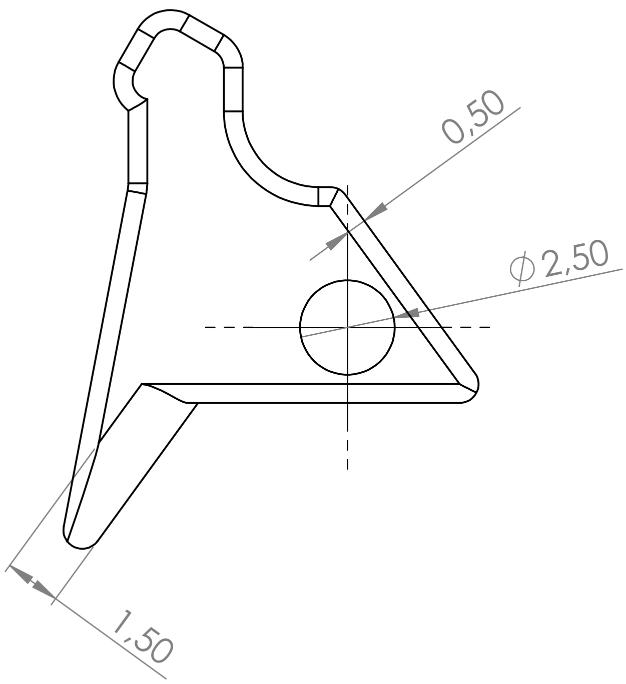
A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1





Nabewerking op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Enkel begrenzing max extension (1x)

MATERIAL: Stainless Steel (4mm thickness)

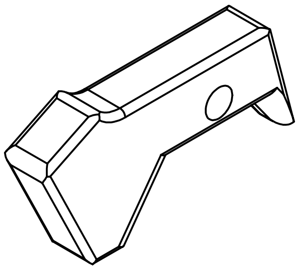
DWG NO.

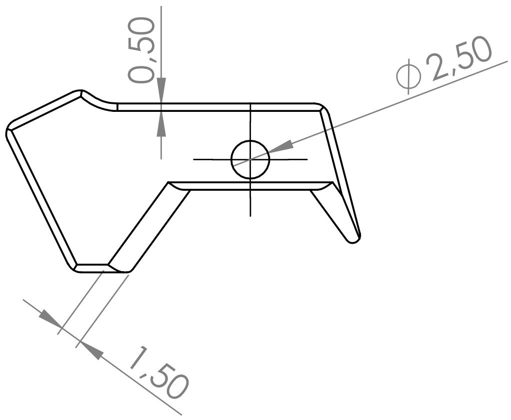
A4

WEIGHT:

SCALE:5:1

SHEET 1 OF 10





Nabewerkingen op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE: Elleboog begrenzin min flexion (1x)

MATERIAL: Stainless Steel (4mm thickness)

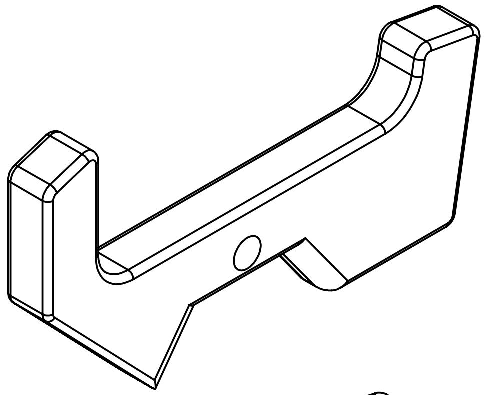
DWG NO.

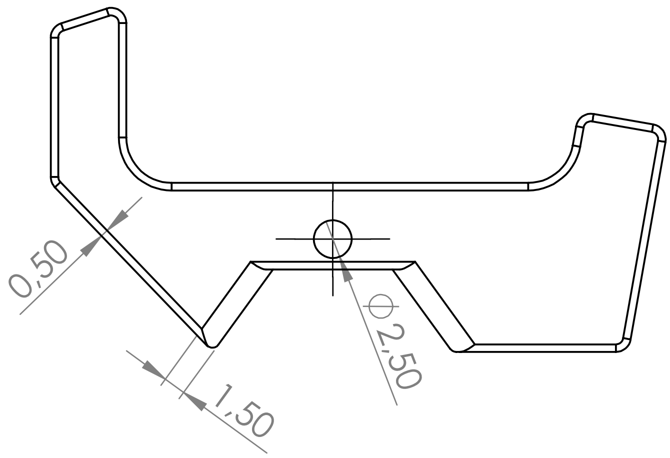
A4

WEIGHT:

SCALE:2:1

SHEET 2 OF 10





Nabewerking op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:
Enkel begrenzing min flexion, extension (1x)

MATERIAL:
Stainless steel
(4mm thickness)

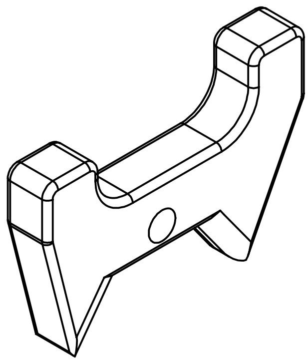
DWG NO.

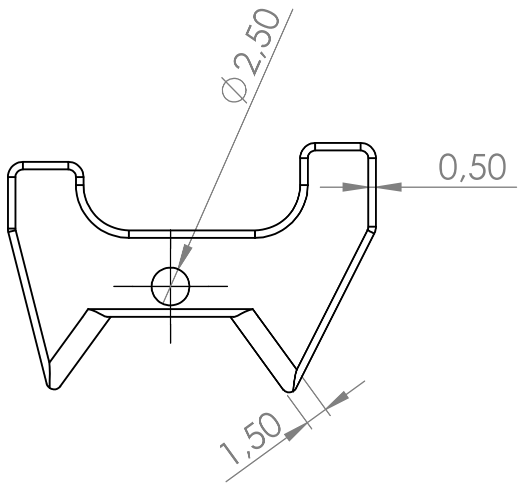
A4

WEIGHT:

SCALE:2:1

SHEET 3 OF 10





Nabewerkingen op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Enkel begrenzing min inversion eversion (1x)

MATERIAL:
Stainless Steel
(4mm thickness)

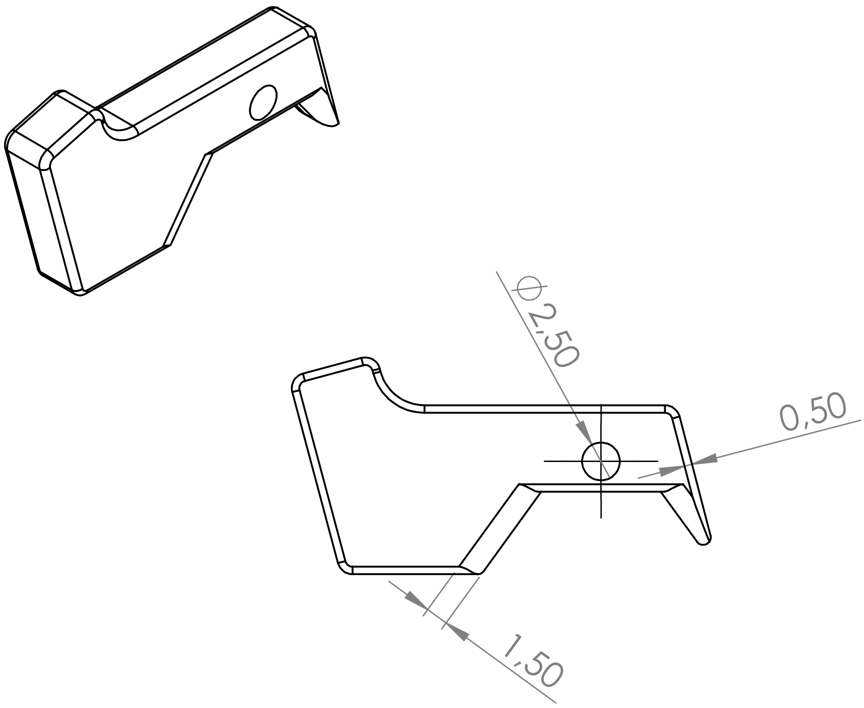
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 4 OF 10



Nabewerkingen op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: Stainless Steel (4mm thickness)

WEIGHT:

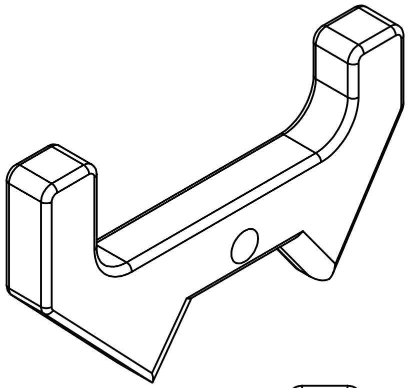
TITLE: Knie begrenzing min flexion (1x)

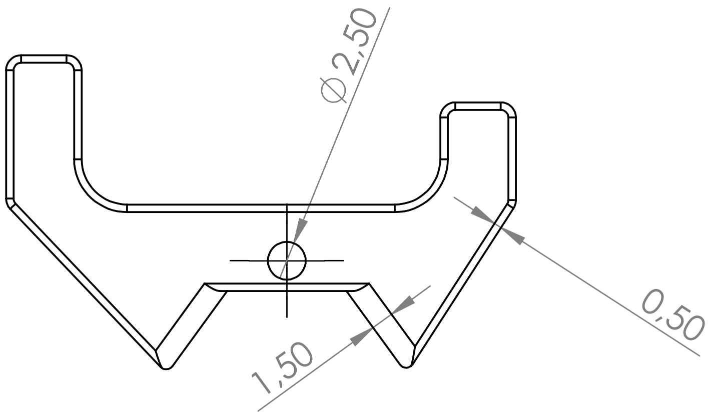
DWG NO.

A4

SCALE:2:1

SHEET 5 OF 10





Nabewerkingen op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Pols begrenzing max abduction adduction (1x)

MATERIAL: Stainless Steel (4mm thickness)

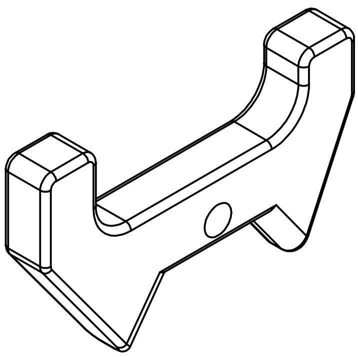
DWG NO.

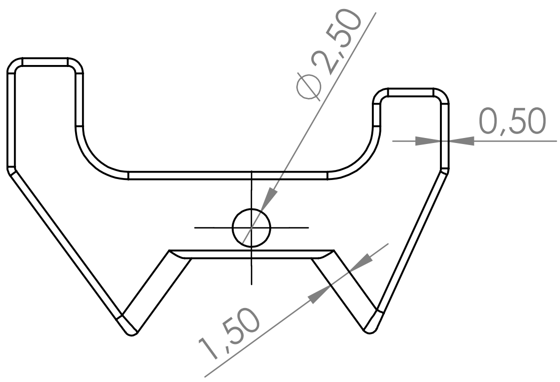
A4

WEIGHT:

SCALE:2:1

SHEET 6 OF 10



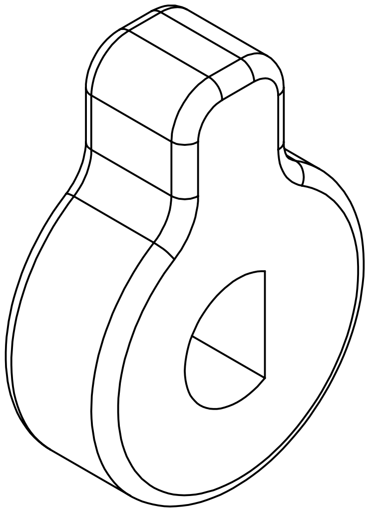


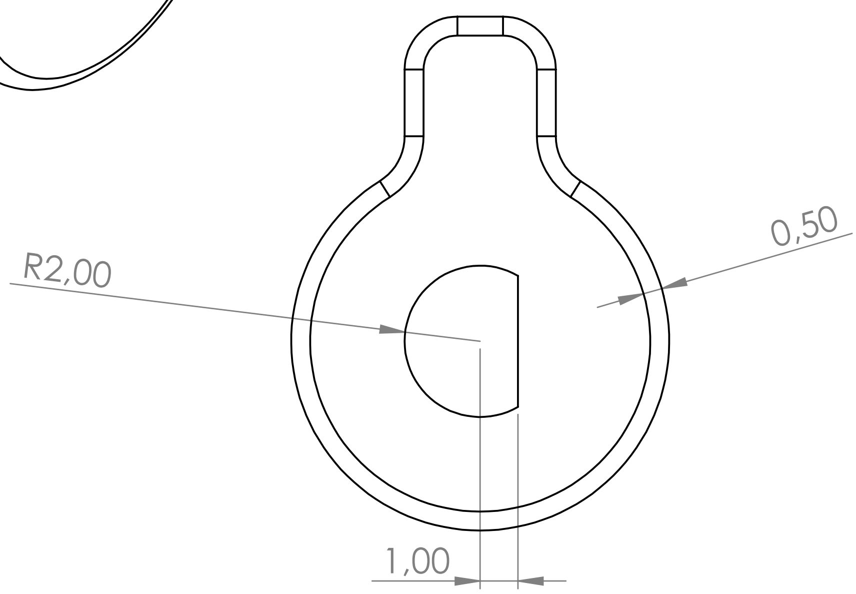
Nabewerking op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE: Pols begrenzing min abduction adduction (1x)	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: Stainless Steel (4mm thickness)	DWG NO.	A4
				WEIGHT:	SCALE:2:1	SHEET 7 OF 10

4 3 2 1

F E D C B A

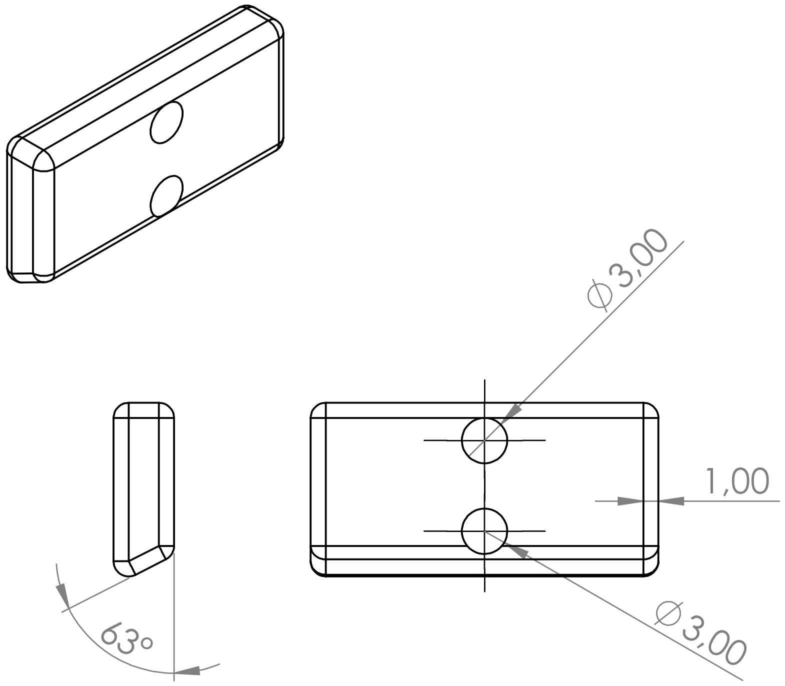




Nabewerkingen op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE	TITLE: Asbegrenzing schouder en heup (1x)
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				
MATERIAL: Stainless Steel (4mm thickness)				DWG NO. A4
WEIGHT:				SCALE:5:1 / SHEET 8 OF 10



Nabewerkingen op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:
Heup begrenzing max abduction (1x)

MATERIAL:
Stainless Steel
(4mm thickness)

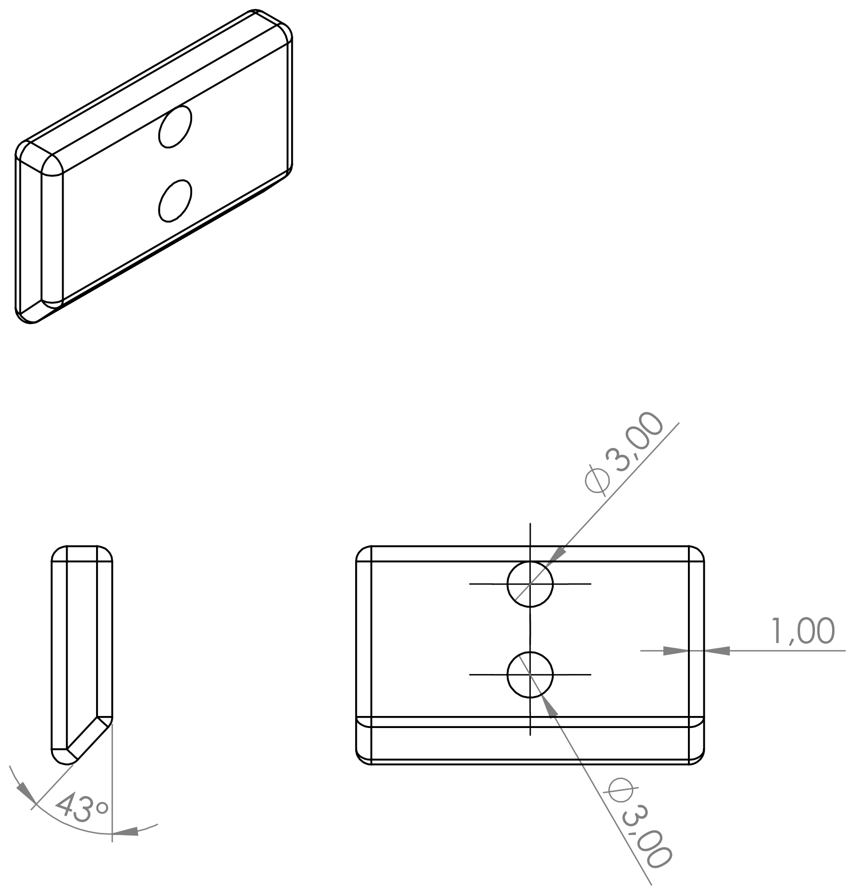
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 9 OF 10



Nabewerkingen op basis van lasergesneden deel

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:

Heup begrenzing min abduction (1x)

MATERIAL: Stainless Steel (4mm thickness)

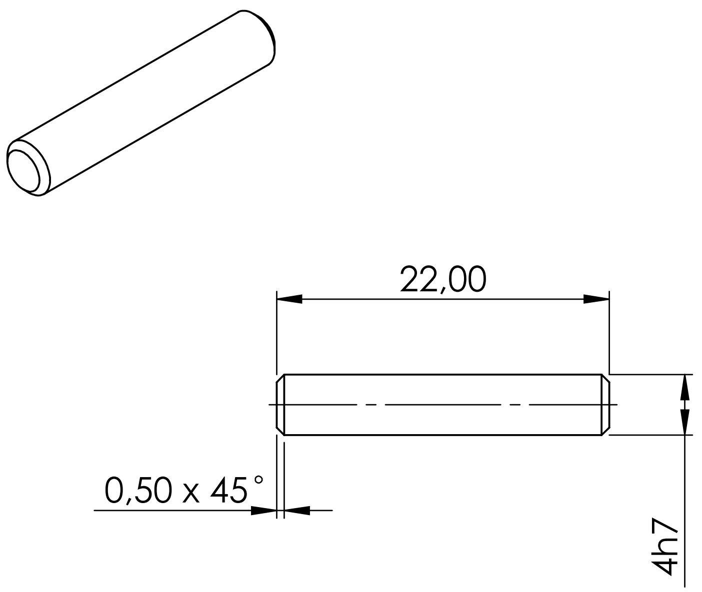
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 10 OF 10



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE: As enkel pols, knie, elleboog, heup, schouder (3x)

MATERIAL: Stainless Steel

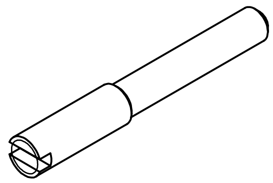
DWG NO.

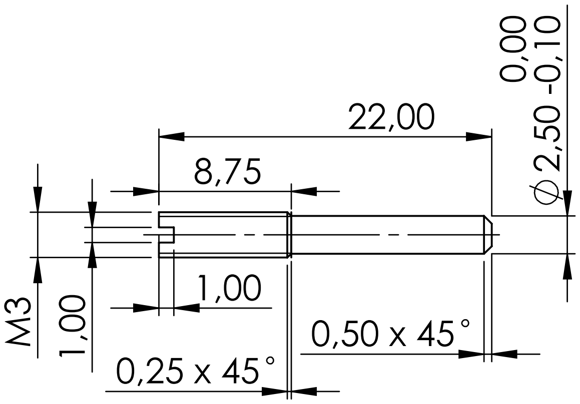
A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 8





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:
Enkel, pols, knie, elleboog blokkadeas kleine bewegingen (2x)

MATERIAL:
Stainless Steel

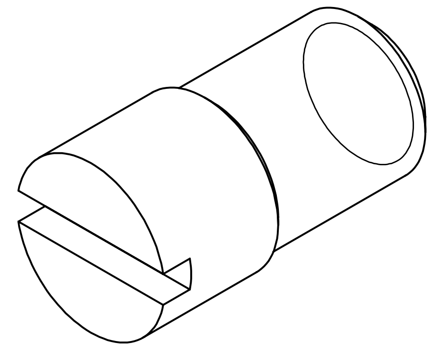
DWG NO.

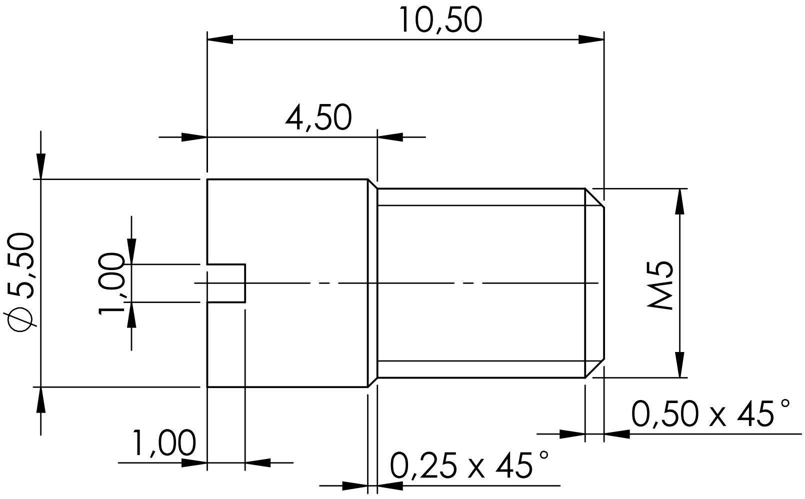
A4

WEIGHT:

SCALE:2:1

SHEET 2 OF 8





Kan worden gemaakt van een bestaande bout

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Enkel, pols pin voor blok (2x)

MATERIAL: Stainless Steel

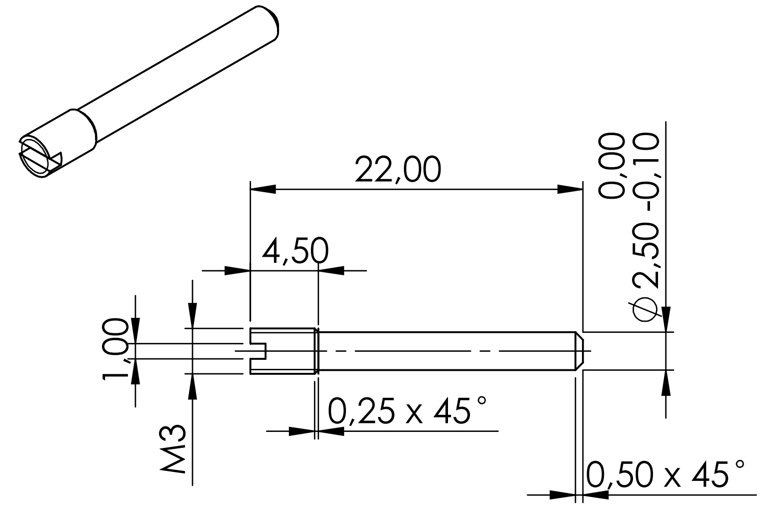
DWG NO.

A4

WEIGHT:

SCALE:5:1

SHEET 3 OF 8



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Blokkadeas knie, elleboog (2x)

MATERIAL: Stainless Steel

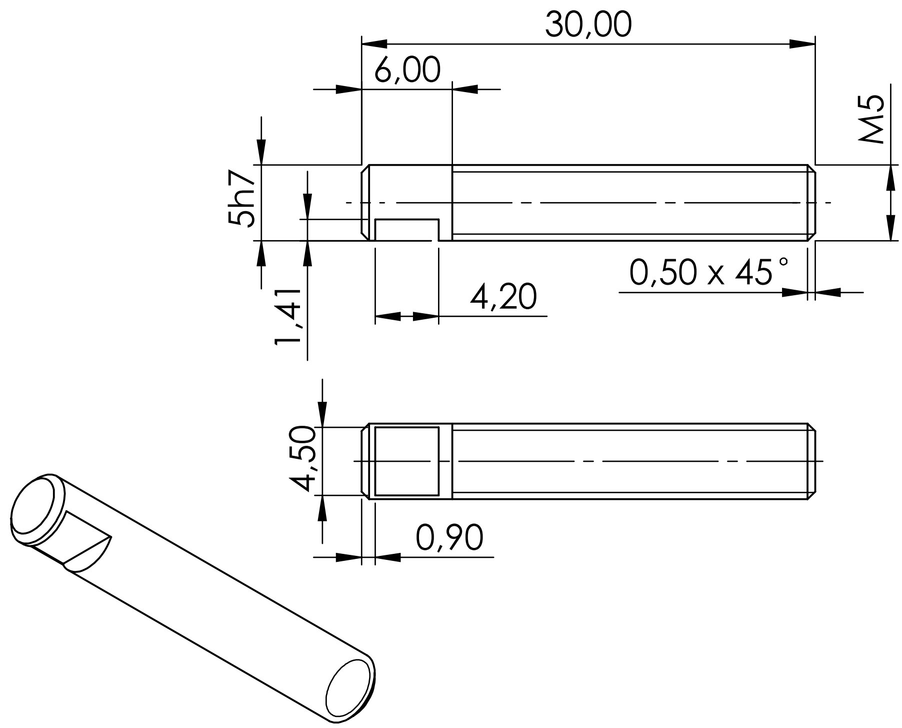
DWG NO.

A4

WEIGHT:

SCALE:2:1

SHEET 4 OF 8



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Bevestigingspin gewricht aan lichaam (3x)

MATERIAL: Stainless Steel

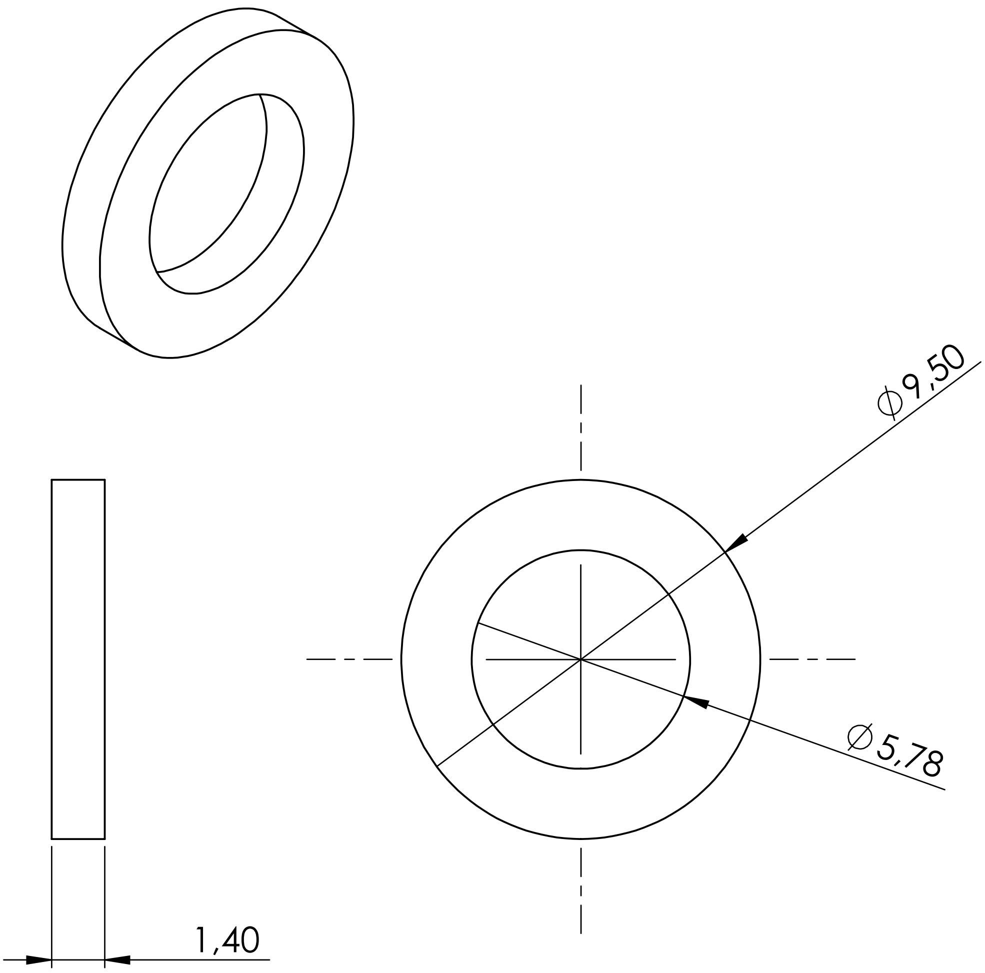
WEIGHT:

DWG NO.

A4

SCALE:2:1

SHEET 5 OF 8



Kan worden gemaakt van een bestaande ring

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE: Ring part bevestiging aan lichaam (2x)

MATERIAL: Stainless Steel

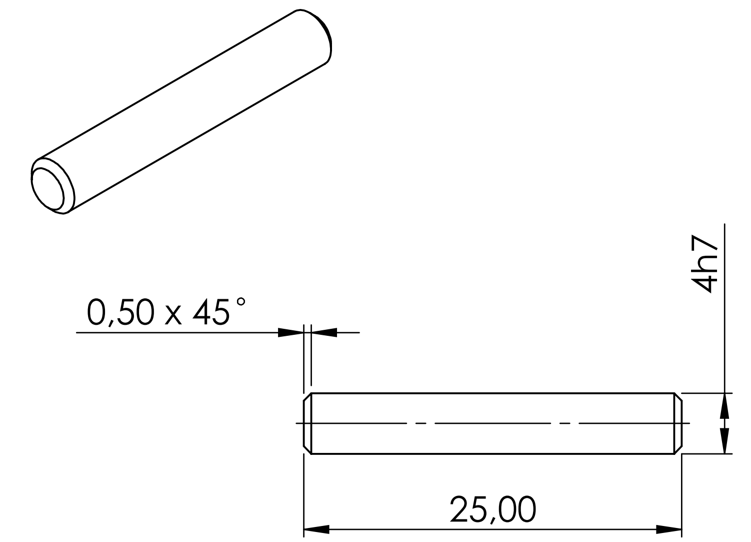
DWG NO.

A4

WEIGHT:

SCALE:5:1

SHEET 6 OF 8



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING — REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Pin bevestiging gewricht aan lichaam (3x)

MATERIAL: Stainless Steel

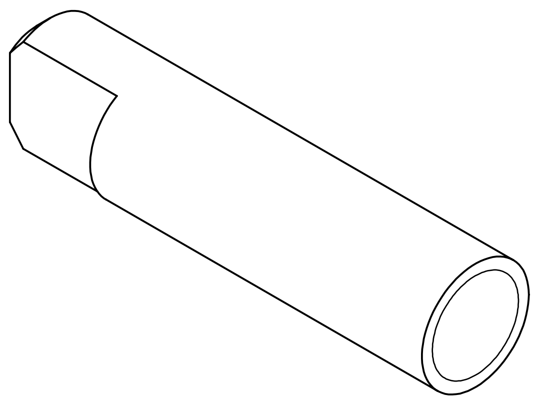
DWG NO.

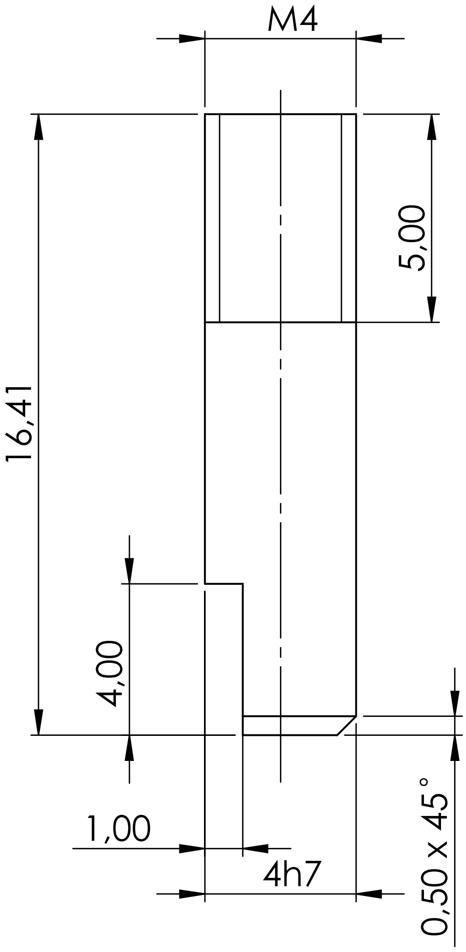
A4

WEIGHT:

SCALE:2:1

SHEET 7 OF 8





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

As heup en schouder (1x)

MATERIAL: Stainless Steel

DWG NO.

A4

WEIGHT:

SCALE:5:1

SHEET 8 OF 8

E.6. List of parts to be bought

The additional parts which need to be bought are:

- Ball bearings (7x4x2.5mm) (8x)
    - Miniatuur Kogellager MR74 ZZ (4x7x2.5mm), Lagerkoning
- Socket set screws (M4x0.7x10mm) (3x)
- Flat head screws (M3x0.5x16mm) (4x)
- Flat head screws (M3x0.5x6mm) (6x)
- Pan slot head (M3x0.5x8mm) (2x)
- Spacer rings (M3) (6x)
- Spacers (M3x5mm) (4x)