Control Engineering Intership

Control of an Exoskeleton
Improvement of the Sitting Down and Standing Up Motions

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Summary

This internship focused on enhancing the sitting and standing movements of Wandercraft's Personal Exoskeleton. The sit-down trajectory generation was improved by making modifications to the constraints and cost functions, resulting in smoother and more comfortable movements. Enhancements were also made to repositioning of the robot on the chair by adjusting its controller architecture and refining the trajectory generation. Generating the trajectories partially in real-time improved tracking precision and allowed for greater flexibility in achieving the final position. These changes contributed to more natural and flexible motions, increasing compatibility with chairs of different heights.

Resumé

Ce stage s'est concentré sur l'amélioration des mouvements d'assise et lever du Exosquelette Personnel de Wandercraft. La génération de trajectoires d'assise a été améliorée en modifiant les contraintes et les fonctions de coût, ce qui a permis d'obtenir des mouvements plus fluides et plus confortables. Des améliorations ont également été apportées pour repositionner le robot sur la chaise en ajustant l'architecture de son contrôleur et en affinant la génération de trajectoires. La génération des trajectoires partiellement en temps réel a amélioré la précision du suivi et a permis une plus grande flexibilité dans l'obtention de la position finale. Ces changements ont contribué à des mouvements plus naturels et plus souples, améliorant la compatibilité avec des chaises de différentes hauteurs.

Resumo

Esse projeto se concentrou no aprimoramento dos movimentos de sentar e se levantar do Exoesqueleto pessoal da empresa Wandercraft. A geração das trajetórias foi aprimorada por meio de modificações nas restrições e funções de custo, resultando em movimentos mais suaves e confortáveis. Também foram feitos aprimoramentos no reposicionamento do robô na cadeira, ajustando a arquitetura do controlador e refinando a geração da trajetória. A geração das trajetórias parcialmente em tempo real melhorou a precisão do rastreamento e permitiu maior flexibilidade na obtenção da posição final. Essas alterações contribuíram para movimentos mais naturais e flexíveis, aumentando a compatibilidade com cadeiras de diferentes alturas.

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The original report is confidential. This is a greatly reduced version meant for publication. Some sections were removed completely while others had some paragraphs redacted. This is not representative of the original work.

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Glossary

Exo	The developed exoskeleton
DC++	Internally developed trajectory generation framework based on the direct collocation method
CoM	Center of mass
CoP	Center of pressure
Freeflyer	Frame of the robot used to indicate the translation and rotation
Contact frames	Frames of the robot in contact with an exterior surface, constraining its motion
Dummy	Mannequin used to represent a human in the exo
URDF	Unified Robot Description Format
IK	Inverse Kinematics

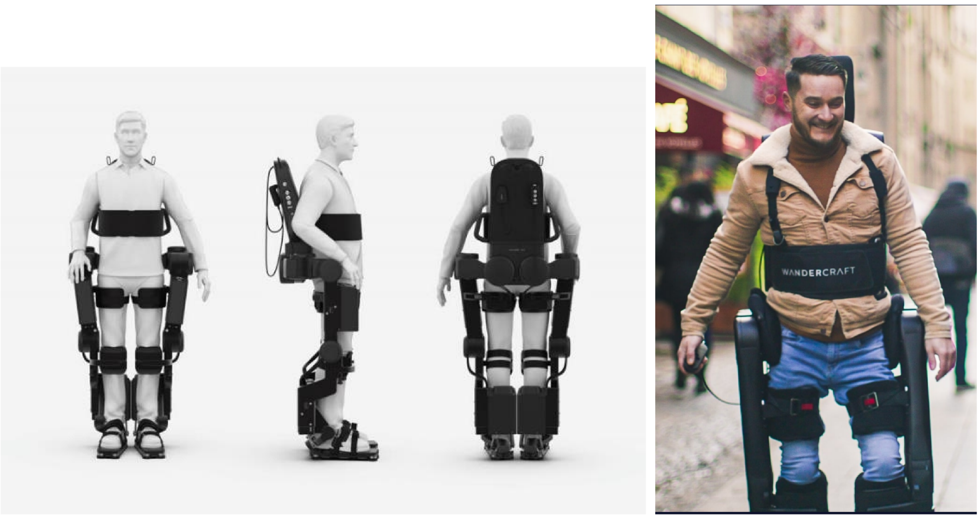
1 Introduction

1.1 About Wandercraft

Wandercraft is a French technology company established in 2012 by three École Polytechnique alumni. The company is dedicated to pioneering cutting-edge lower-body robotic exoskeletons (or just *exo* as they are called internally). Its primary goal is to use these exoskeletons to assist individuals with physical disabilities in regaining mobility and the ability to walk.

Presently, Wandercraft business goals focuses on the production and commercialization of the Atalante X exoskeleton (Figure 1a). This model serves as a medical device augmenting physiotherapy sessions. It helps patients to stand and walk without the need of clutches. But with Atalante being a CE certified and commercialized medical device, efforts are directed mostly towards sales, maintenance and support, rather than research and development.

The company's research and development endeavors primarily revolve around Personal Exoskeleton (Figure 1b). Designed for everyday use rather than clinical environments, It aims to provide an alternative to wheelchairs, emphasizing the advantages of an upright posture. Extensive attention is dedicated to further advancing this technology and capabilities, with the intention of enhancing mobility and quality of life for users.



(a) Atalante (b) Personal Exoskeleton

Figure 1: The Atalante and Personal exoskeletons.

1.2 Mission statement

During the internship, my primary objective was to improve the sitting and standing motions of the platform. To achieve this goal, I engaged in a comprehensive exploration of various possibilities for improvement. Some of these were deemed unfeasible, while others were deferred due to their lower priority. Nevertheless, several improvements were successfully integrated into the exoskeleton.

The significance of achieving a refined sitting motion is heightened by the fact that Wandercraft unveiled it's Personal Exoskeleton to the world at a live demonstration in New York in December 2023. This keynote presentation represents the first official introduction of the exoskeleton to the public, making it a central event that can significantly influence the company's future.

The contents of this report are structured as follows: In Section 2 I briefly present the platform and the main internal tools used during this internship. Section 3 details the implementation of a smoother sitting motion, which is not only more comfortable but also feels more natural. Finally, in Section 4, I describe the modifications made to the standing motion to enhance user comfort, I also describe a proof of concept to allow a standing motion from various chair heights.

2 Materials and Methods

2.1 The platform

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2.2 Software tools

2.2.1 Trajectory generation

The exo's movements, including the sitting and standing motions, primarily follow a trajectory generated offline. This process is facilitated by the DC++ framework, an internally developed tool based on the direct collocation method. This optimal control technique discretizes time into collocation points, approximating state and control variables with polynomial splines. This way the problem is transformed into a nonlinear programming task solvable by standard optimization algorithms.

Sometimes we want to have trajectories which can be divided into moments of qualitatively different behaviours. Within the DC++ framework, we can define multiple domains where each domain is characterized by a unique set of constraints, cost functions, and contact frames.

2.2.2 Simulation environment

To reduce the reality gap between simulations and experiments, Wandercraft slowly transitioned away from the well-known Gazebo simulator in favor of Jiminy [1], an open source and cross-platform simulator for poly-articulated systems. To compute how the robot moves, the simulator uses the library *Pinocchio* [2] and takes into account an URDF (Unified Robot Description Format), a file containing information about the geometrical model of the robot such as the kinematic chain, link weights, etc.

This simulation environment facilitates the initial stages of algorithm development and controller tuning, reducing the necessity to use the limited supply of R&D exoskeletons.

2.2.3 *Logstudio*

Logstudio is the software used to analyze data from experiments. It synchronises the text logs with experiment videos and data plots. It offers insights into joint parameters, including position, velocity, acceleration and torques. Additionally, it provides information about the freeflyer position and rotation.

2.3 Experimental setup

To increase safety and reduce risks, several steps must be taken before testing any modifications to the behaviour of the exoskeleton with a real user. After the algorithms are developed and fine-tuned through simulation, tests are carried out employing a dummy that emulates a human patient.

Once safety is confirmed, the algorithm can be tested on an able-bodied individual better equipped to handle unexpected situations, such as the exoskeleton assuming uncomfortable positions.

After we are confident that all potential risks have been mitigated, we invite Kevin to test the exo with the new algorithms. Kevin is a paraplegic individual who has been a part time employee for over four years. He works as an exoskeleton pilot and evaluates the platform's behaviour, providing valuable feedback regarding his user experience. This iterative development process is illustrated in Figure 2.

3 Improvement of the Sitting Motion

During the investigation of the sitting from Active Balance, it was noted that one of the causes for the falling sensation was the the fact that the exo's back went aggressively from a $40^{\underline{o}}$ pitch to $0^{\underline{o}}$ pitch. The two past investigations, quasi-static sitting and squat to sit movement showed us that one way to reduce the feeling of falling was to reach the chair with a bent back (positive pitch) instead of a straight back.

Finishing with a positive pitch also makes the movement seem more natural, this is how we usually do it when we sit down carefully. It also decreases the pitch velocity during a fall and makes the movement smoother.

Finally, in order to reach a final comfortable sitting position (with a straighter back), the repositioning controller was improved to feel more natural.

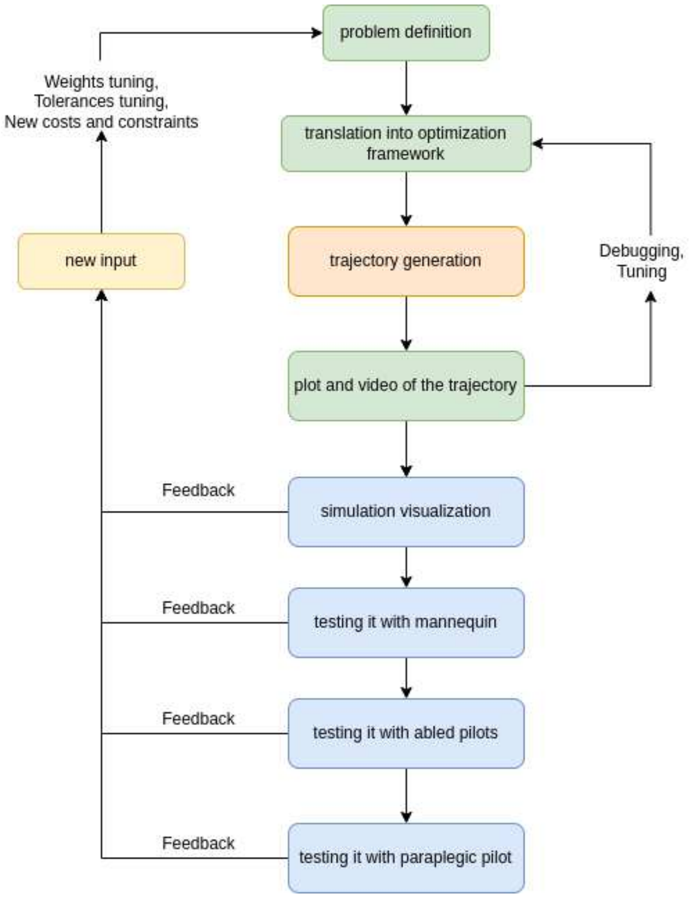


Figure 2: Iterative development and testing framework. Image taken from [3].

3.1 New trajectories

Two new trajectories were proposed to be compared with the nominal trajectory.

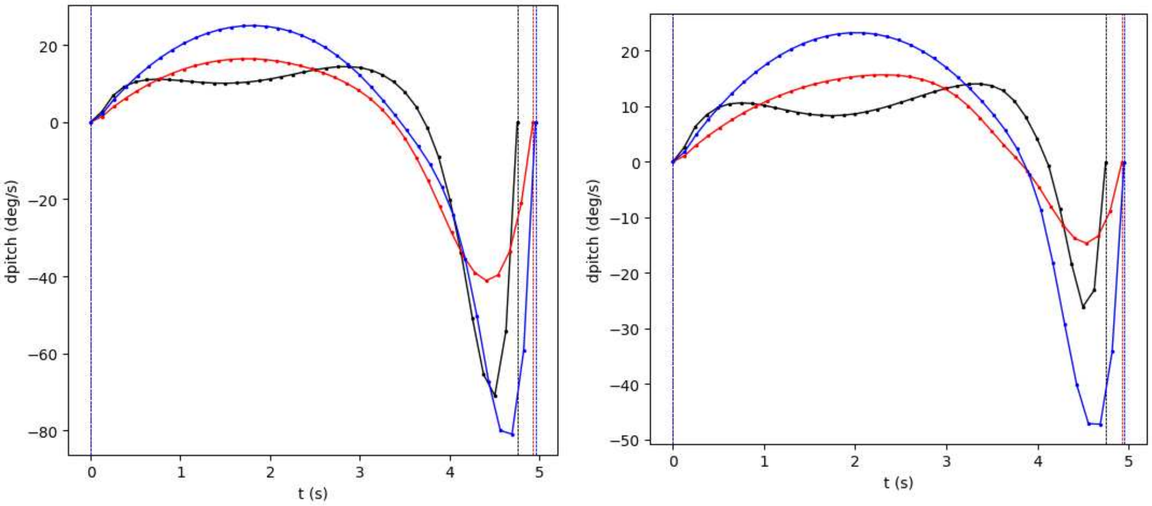
Both had an increased acceleration weight and lower torque weight in the cost function of the optimisation problem. One also allowing the robot to have a higher pelvis pitch when going down as this usually makes the trajectory more stable. The parameters for the three trajectories can be seen in Table 1:

Table 1: Parameters of the three proposed trajectories.

Trajectory	**Torque Weight**	**Acceleration Weight**	**Max Pitch**
Nominal	10	1	40º
Accel Cost	1	10	40º
Max Pitch	1	10	60º

The sagittal joints are symmetrical and there were no considerable changes in the other planes of motion, thus we can focus the analysis to the right sagittal joints. Figure 3a shows the right sagittal joints for the three generated trajectories. We can see that Accel Cost (in red) has a smoother trajectory compared to the other two. It seems that minimizing acceleration during the motion by increasing its weight in the optimisation function managed to remove unnecessary movements.

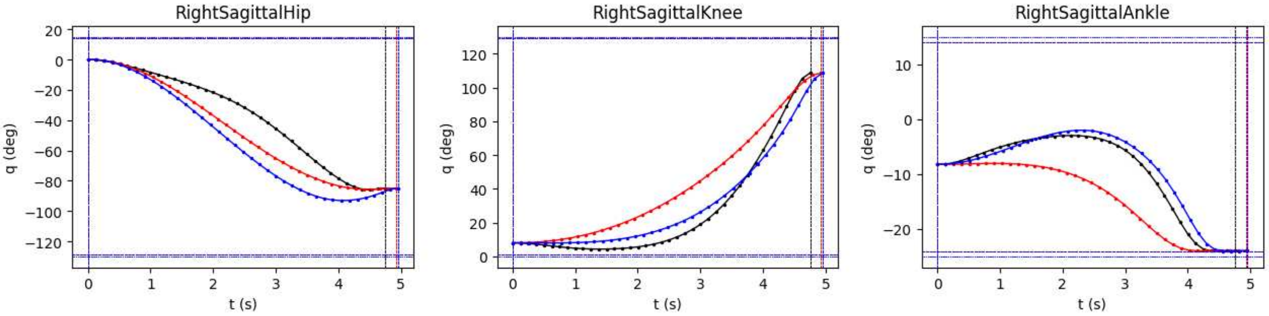
Surprisingly, even if we decreased the torque weight, Accel Cost still managed to have smaller maximum torque than the other two trajectories (Figure 3b).



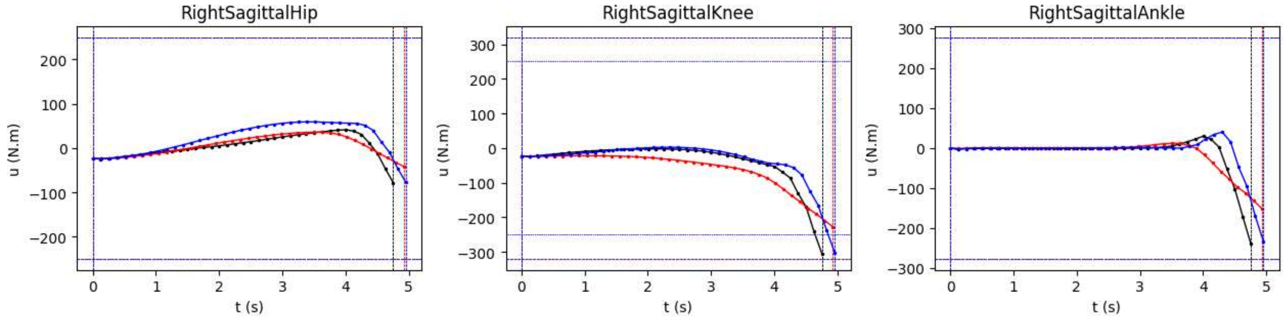
(a) Without positive pitch.

(b) With a 30º positive pitch.

Figure 4: Pelvis pitch for the 3 trajectories of interest: Nominal (black), Accel Cost (red) and Max Pitch (blue).



(a) Positions



(b) Torques

Figure 3: Right sagittal joints positions and torques for the 3 trajectories of interest: Nominal (black), Accel Cost (red) and Max Pitch (blue).

3.2 Positive pitch

After tuning the trajectory generation to obtain two additional trajectories, we wanted to modify the generation script to accept variable final pelvis pitches.

When we compare the same three trajectories with and without a 30º positive pitch, we can see that in all cases by having a positive pitch we can considerably reduce the maximum angular velocity as seen in Figure 4.

These results where promising, making the trajectories considerably smoother and being far from saturating the torque.

3.3 Sitting height computation

The previous method considered that the sitting point touches the chair at the end of the trajectory. As this is only the case when the trajectory finished with a straight back, we needed to change how we tell DC++ our desired chair height. Instead of using the sitting point, we used the pelvis as a reference for the height constraint. This approach helped us avoid being dependent on the pitch. In other words, we can now say that the desired pelvis height is the chair height plus the hip radius.

After making changes to how we calculate the sitting height during the trajectory generation, we also had to update it in the controller. Previously, the `computeSittingPointHeight()` function was used to determine the height of the sitting point relative to the feet. However, since we realized that the sitting point is no longer the contact point with the chair, we replaced this function with a new one called `estimateSittingHeight()`. This new function also calculates the height of the hips by subtracting the hip radius from the pelvis height and then returns the lowest value between that and the sitting point height.

3.4 Validation with Kevin

After having tuned the parameters in simulation and verified its performance with the Dummy it was time to validate them with Kevin.

We wanted to confirm with him 2 things:

- Which of the 3 possible trajectories he felt was better?
- Did he like the positive pitch? If so, which angle did he feel most comfortable with?

In both the Nominal and Max Pitch trajectories, he felt his stomach being pressed by the support jacket. The Accel Cost didn't have this problem and was considerably smoother than the Nominal trajectory, almost not having a falling phase. Therefore, the choice of continuing the tests with the Accel Cost trajectory was straightforward.

Having decided on the new trajectory, we tested it with different final pitch angles.

Kevin felt that the positive pitch made the trajectory smoother overall. However, he complained that a 30º pitch caused discomfort when the exo pressed against his back as he tried to straighten it immediately. While the issue was less pronounced with a 15º pitch, to mitigate this discomfort, we ultimately decided on a 10º pitch as a good trade-of.

This experiment validated and consolidated the Accel Cost with a 10º positive pitch as the new nominal trajectory for further developments.

3.5 Improvement of the repositioning

Previously, we acknowledged that finishing the sitting trajectory with a positive pitch allowed a smoother motion by decreasing the maximum pitch angular velocity.

But by doing this a new problem arises: the repositioning algorithm was not adapted to this new final sitting position. The repositioning also didn't feel very natural as it always caused the robot to push the chair backwards and slide it's feet on the ground. In a real world use of the exo, displacing the chair means possibly damaging the floor. Be it because the chair actually slides or because we have a fixed bench and the feet of the exo slide. So we took this opportunity to rework the repositioning algorithm to make it look and feel more natural while reducing the displacement of the chair.

3.5.1 The repositioning controller

Redacted

3.5.2 Origin of the chair movements

As previously mentioned, one of our goals was to reduce the chair movements caused by the repositioning of the robot.

To fix this issue it was important to understand what caused these undesired movements in the previous algorithm. After some analysis we discovered mainly 4 reasons:

1. **High Speed Fall**: whenever the exo finished the trajectory with a high speed, this would transfer to the chair pushing it backwards.
2. **Left Foot Sliding**: sometimes the left foot wouldn't be raised enough thus causing it to slide on the ground.
3. **Left Foot Sinking**: as the desired trajectory is not completely transferable to the real world, at the end of the foot repositioning the left foot would have already arrived at a proper position but the controller would still try to move it, effectively trying to sink it into the ground.
4. **Feet realignment**: at the end of the feet repositioning the controller would want to make sure that the feet are actually aligned and it would move the feet while they were on the ground pushing the chair back.

The first cause was already minimized by having a smoother trajectory with almost no falling. The rest were solved by improving the repositioning by employing the following strategy.

3.5.3 Proposed solution

Repositioning the feet with the exoskeleton's back bent forward is not a viable task. We first needed to add a preliminary phase of repositioning the back before addressing the feet. Additionally, as the movement of repositioning the feet was not as smooth as desired, we made significant improvements to enhance its fluidity.

Finally, we made the decision to eliminate the `reachFinal` step, as it was too constraining. Instead, we opted to implemented a strategy to verify and ensure that the exoskeleton is in an acceptable position at the end of the movement.

3.5.4 Improvement of the back alignment

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3.5.5 Improvement of the feet placement

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3.5.6 The online repositioning

One of the problems with the previous repositioning controller was that the trajectory was completely generated offline, but the actual position of the robot can eventually diverge from the desired trajectory. One noticeable consequence of this is when the robot is repositioning its left foot, the desired trajectory would want it to sink in the floor.

As the trajectory was previously generated by phases and then concatenated, it is straightforward to call each generation online and use the current position of the robot instead of the final position of the previous trajectory. This way we gain more control on how each trajectory is handled by the controller.

The first improvement made was ending the trajectory when the floor is detected while repositioning the foot. To guarantee that the feet align correctly with the floor when this occurs, the ankles are placed in compliant mode. This means that they are no longer under active control and are allowed to move freely when an external force is applied. Consequently, when the exoskeleton's foot touches the ground, we can prevent it from sinking while also enabling the ankles to adjust for a flat-footed position.

Another advantage of implementing online repositioning was the ability to detect the switch from the hips to the sitting point as the contact with the chair in real-time, making this transition even smoother.

Furthermore, it enabled us to eliminate the need for the last part of the trajectory, which was originally designed to ensure that the exoskeleton would reach the target position. Instead, we can now verify if the final position is acceptable and only initiate the final motion if necessary, thereby enhancing the flexibility of the movement while ensuring comfort. For this we implement the `isPositionAcceptable` function which checks that the following conditions are:

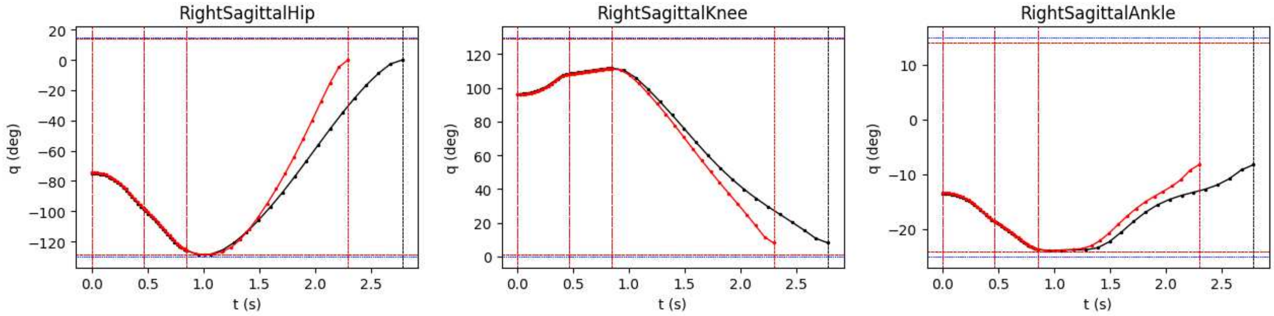
- The knee angle should be greater than 85º.
- The ankle angle should be around zero degrees, with a margin of 5º margin.
- The pelvis pitch should fall within the range of -6º to -3º.
- The final position is symmetric in the sagittal plane.

If any of these conditions are not met, the `reachFinal()` trajectory will be tracked, compelling the robot to move to the target position, even if it results in less fluid movement and a potential impact on the chair.

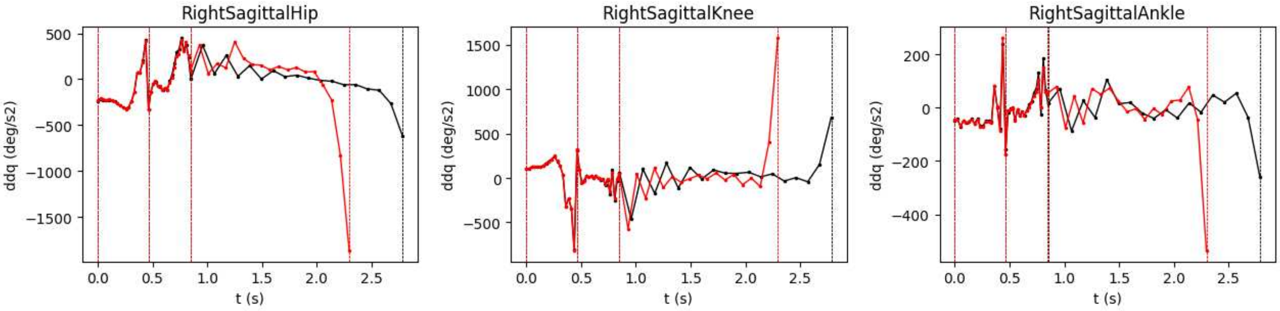
3.6 Conclusions

In the end, we were able to considerably improve the user's experince during the whole motion, from sitting to repositioning. The generated trajectory was smoother and the possibility of finishing it with a positive pitch added another degree of control to it. The improvements made to the repositioning controller, made it look more natural and flexible while reducing chair movement.

4 Improvement the Standing Motion



(a) Positions



(b) Accelerations

Figure 5: Right sagittal joints positions and accelerations for the new trajectory (black) compared to the previous trajectory (red).

4.1 Smooth stand-up

During tests with Kevin he would always complain about the final moments of the standing motion. This happened because the back of the exo would need to go from a position with high pitch to a straight position and then the pelvis of the exo would hurt his lower back. This limited the number of times he could stand up with exo.

To solve this problem we decided to try the same solution as in the case of the smoother sit-down. We added a cost function to the pitch acceleration in the *double support* domain. We also made the movement slower, increasing the minimum and maximum trajectory times by half a second. After some tuning of parameters we achieved a stable trajectory in simulation. The resulting trajectory is indeed slower and the acceleration was greatly reduced.

When testing with Kevin he was extremely pleased. Not only did the violent movement not occur, but oscillations that were usually present at the end of the trajectories also disappeared. It is possible that this last fact is due to them dying out during the trajectory which is longer.

With the new combination of smooth sit and stand movements he was so comfortable that he kept executing the movement by himself even if we didn't have anything else to test.

4.2 Stand-up multi-chair

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5 Conclusions and Further Work

During the course of my internship, I was able to make significant contributions to the prototype. By introducing the possibility of finishing the sitting motion with a positive pitch, we opened up new possibilities for reducing the sensation of falling. This feature, coupled with adjustments to the trajectory's acceleration and torque weights, resulted in an improved sitting motion that offered Kevin a more comfortable experience. Pairing this with the work on the Repositioning controller, the complete sitting motion felt smoother and more natural.

Inspired by our work on the sitting motion, we successfully applied similar modifications to address the sudden pelvis movement in the stand-up motion. By allowing a longer trajectory and by introducing a cost function that minimizes the pelvis pitch acceleration, we were able to eliminate the discomfort felt by Kevin during the stand-up.

Some possibilities for improvement and future work have emerged from the internship experience. Notably, if the chair height is below what was considered for the trajectory generation, the repositioning will start prematurely. This can be solved by ensuring that the chair is detected before starting the movement.

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