Feasibility Study: Towards a Robot-Assisted Gait Training in Ophthalmological Rehabilitation*

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***Abstract*— The idea of using mobile assistance robots for gait training in rehabilitation has been increasingly explored in recent years due to the associated benefits. This paper describes how the previous results of research and praxis on gait training with a mobile assistance robot in orthopedic rehabilitation can be transferred to ophthalmic-related orientation and mobility training for blind and visually impaired people. To this end, the specific requirements for such orientation and mobility training are presented from a therapeutic perspective. Using sensory data, it is investigated how the analysis of training errors can be automated and transferred back to the training person. These pre-examinations are the prerequisite for any form of robot-assisted mobile gait training in ophthamological rehabilitation, which does not exist so far and which is expected to be of great benefit to these patients.**

I. INTRODUCTION

Mobile robotic systems for gait rehabilitation have been gaining in importance since the introduction of the Kinect RGB-D camera. They allow free movement and gait training of the patients even in the clinic environment. Further, the independent and self-reliable training of patients independent of the therapists in the rehabilitation process is becoming increasingly important in times of scarce financial and human resources in public healthcare systems. Patients usually receive instructions and recommendations from therapeutic staff on how to carry out self-training for time slots when no therapies with therapists take place. Although most patients are motivated, they are concerned about safety and proper exercise execution, leading to low number of self-training. In contrast, self-training assisted by a training robot enables patients not only to exercise independently of the presence of a therapist, but also to receive recommendations for correction concerning their training, including positive feedback. In this way, training errors are avoided, and the progress of the therapy is strengthened. Usually, this "supervised" self-training results in faster rehabilitation [1]. Two examples were already demonstrated: a first one for walking and orientation self-training of stroke patients in late stages of the clinical post-stroke rehabilitation was realized in [2], [3] and further, a mobile robot for self-training assisted patients after orthopedic operations in clinical aftercare with personalized gait exercises [4], [5].

The ophthalmological rehabilitation is a further potential field of application for which the opportunities and benefits of using a mobile robot-assisted self-training will be investigated by a feasibility study. The research question of this paper is if it is possible to observe persons exercising during an orientation and mobility (OaM) training (see figure 1) with a simple 2D laser scanner and a 3D depth camera (see figure 2 left) and to determine deviations from the intended behavior during the exercises with the necessary accuracy. The results presented in this paper will form the basis for the implementation of a robotic training system (see figure 2 right) that can observe the patients during training by means of its onboard sensor system, can actively guide or follow them by means of its mobility, can recognize errors in the gait training process and intervenes to correct them, and finally records the course and progress of the training.

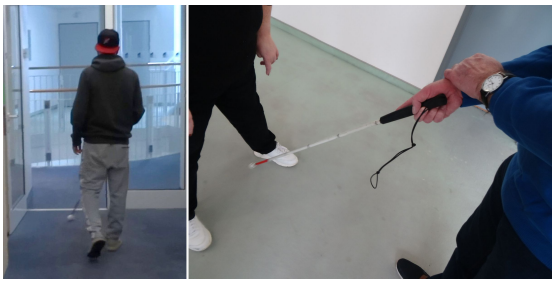

Fig. 1. Visually impaired patients during their orientation and mobility training in the rehabilitation clinic Masserberg. **Left:** patient while training hazard avoidance walking and orientation. **Right:** training the correct usage of the white cane guided by a rehab teacher.

The remainder of this paper is organized as follows: section II first discusses related work in the field of mobile rehabilitation robotics with the focus on gait analysis in different application areas. In section III, the main aspects of OaM training of visual impaired and blind people which could be done in robot-assisted self-training are explained from a rehab teacher's point of view. It will be discussed which therapeutic and methodical aspects of an existing orthopedic gait training system can be reused for OaM. Two OaM aspects will be selected as use cases for feasibility investigations. In section IV, the experimental setup is presented together with the data obtained regarding assessing the selected uses cases. Section V discusses next steps towards the final application using a mobile robot.

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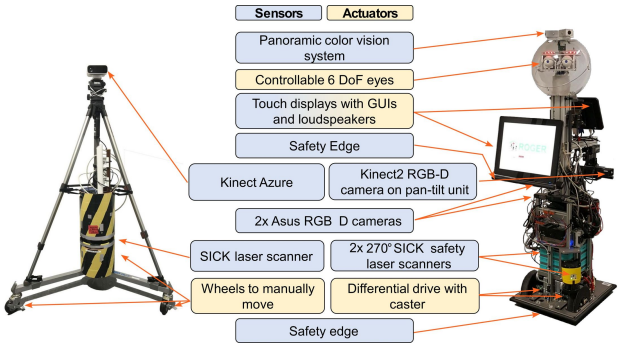

Fig. 2. **Right:** Mobile robotic platform for gait training already used in neurological and orthopedic rehabilitation applications. **Left:** Experimental platform with sensors similar to those of the robotic platform.

II. STATE OF THE ART

Even if mobile robotic systems for gait rehabilitation have been gaining in importance since the introduction of the Kinect, research in this area is still largely concerned with accuracy studies of derived gait characteristics, such as step length when using the 3D image-based sensors on-board a mobile robot. Further research concerns a suitable position of the camera to observe the gait training person for skeleton extraction under usage of a camera specific software development kit (SDK)[1]. Also, most of this research is done under laboratory conditions. Examples for feasibility studies concerning accuracy tests and extraction of gait features in gait training using a mobile robot are [6], [7], [8]. Mostly, these approaches do not include patients. If there is a comparison of accuracy, it is carried out against a Vicon system with multiple calibrated infrared cameras and markers for the lower body.

In the application field of neurological gait training, there are only few works with usage of mobile robotics, typically for stroke and parkinson's rehabilitation. In [9], different gait patterns for stroke patients and older people are discussed. Further, the projection of the target point for a respective next foot strike, a rhythm prescription for the gait and vibration elements attached to the patient's body to teach postural errors are considered. In [10], an approach to detect the freezing of parkinson's patients by a mobile robot that follows the patient is discussed. In our own work [3], the objective was to mobilise stroke patients in a real clinic environment, that is why gait analysis was not focused on.

In the field of orthopedic gait training, two objectives are known: the analysis and correction of the gait patterns and the correct use of walking aids. In [11], the kinematic features acceleration and jerk obtained from two static cameras are discussed to evaluate the gait on underarm crutches as stable. The work in [12] has a similar objective where a robot vacuum cleaner as the basis of an attached camera is used, so that the test persons can walk longer distances on underarm crutches. In our own work [13], the correct usage of the crutches in weight-relieving three-point gait was analysed and corrective feedback to the patient was given. Concerning gait analysis in orthopedic applications with mobile robots, only our own work is known so far [4], [5]. There, the positive effect of a training robot in self-training after hip endoprosthetic surgery was shown with the main focus on training of the correct use of forearm crutches, the training of a symmetrical step length and stance duration, keeping an upright upper body posture, and performing correct movements in the hip and knee joints.

Published research work in ophthalmologic applications using mobile robots for gait training are not known yet.

In addition to the methodological-technical studies, purely sociological studies are also being carried out. Research typically uses commercially available robots such as Pepper or Double, which do not have sufficient on-board sensors and computing capacity for gait analysis. They therefore focus on research aspects of motivation, feedback or acceptance. Exemplary approaches are presented in [14], [15], [16].

III. ORIENTATION- AND MOBILITY TRAINING

The objective of the orientation and mobility (OaM) training is to train the use of the white cane (cane) for blind and visually impaired people so that they can move around independently in an upright and low strain posture. In addition to the perception of dangerous situations, obstacles and structures of the pavement using the cane (aspects of mobility), it is also an aid for recognising environmental information and orientation points (aspects of orientation).

In order to realise the aspect of mobility, different techniques of using the cane, such as the sliding technique (see figure 1) or the two-point technique have to be trained. In addition, the patients must hold the cane in front of the body in a certain way: the so-called working posture. In addition, they also have to maintain an upright posture. Furthermore, mobility also means dealing with potentially hazardous situations such as climbing stairs or opening and passing through doors.

In contrast, orientation training aims the exploration of the environment to enable the patient forming an internal model of it. The feasibility study presented here is limited to indoor environments mainly because of the planned robot-assisted indoor training application. In summary, the main focus of the study is to establish a robot-assisted training approach to guide and to support the patient during OaM self-training.

A. Rehab teachers' objectives for OaM training

For OaM training, rehab teachers take into account the following important aspects during training sessions which are supposed to enable the patients to move in a directed way that avoids hazards and obstacles.

Cane movement to detect hazards and obstacles on the walking path: One of the most important techniques to check firstly the accessibility of the terrain with a cane before taking a step is the sliding pendulum technique. If a step is to be taken with the left foot, the cane which is in front of this foot has to be moved on the ground in front of the right foot simultaneously with lifting the left foot and vice versa

[1]https://learn.microsoft.com/en-us/azure/kinect-dk/body-joints

for the next step with the right foot. The cane is moved about three steps in front of the person in order to be able to stop the movement in time when detecting a hazardous situation. The width of the pendulum is about the width of the shoulder plus a few centimeters on each side. This makes it possible to control the walking area only, but not unnecessary areas around the person. The shape of the movement from side to side should be uniformly accelerated. It should also be noted that a visually impaired or blind person should never walk backwards as the area might not be checked. The training of such a sliding pendulum rhythm can also be done while standing with only indicated steps (see figure 1 right).

Holding the cane while moving: The cane is held in front of the upper body, whereas only the middle finger serves as a clock for the pivot of the cane in the sliding pendulum technique. It is important that the arm and the hand are kept immobile during the movement. This basic holding technique (working posture) is the only way to ensure that the relevant walking area can be scanned and at the same time the wrist is protected from overload.

Climbing and descending stairs: When climbing stairs, the patient moves until the tips of the feet hit the first step. The cane is lifted vertically and moved forward until it hits the next step and then the step after that. At this height and distance the cane is hold hanging loosely. Then one step is climbed with one foot while the cane swings forward to indicate the next step. By having the cane two steps upfront, a misstep into space is avoided when reaching the last step. When descending stairs, after detecting the first step of the staircase with the cane, it is approached and the cane is gripped to a vertical position. The cane has to move along the edge and further to detect the end of the second step. In this position, the working posture is assumed again. While stepping down the staircase the cane is also moved down the stairs with a slightly floating inclined cane. The last step is detected when the cane hits the floor again.

Another important outcome of OaM training is the persons' ability to orientate themselves in their environment. Here, the learning to orientate is limited to indoor environments, although OaM training also considers outdoor areas.

Exploring the indoor environment: To create an internal environment model, the environment must be safely explored, and the location of important landmarks must be recognised. In training, a first simple way to orientate is to move along reference points such as walls. Also, the person must be able to make defined turns, which is why learning a 90° *turn* is important. To *identify objects* the vertically held cane has to be moved along the object to determine its shape. Also, for narrow corridors a vertical cane posture yields more information about the environment. Otherwise, the rehab teacher's position is mainly characterised by the observability of e.g. cane deflection, body and cane posture of the person to be trained.

B. Transferability of an orthopedic gait training

It will be discussed which approaches and methods from own previous work on robot-assisted orthopedic gait training [4], [5] can be re-used for OaM training. Originally, the subset of gait characteristics defined in orthopedic rehabilitation that the robot must be able to reliably recognise contains step length, stance duration, step width, flexion/extension of knee and hip joints as well as the crutch position which is not supported by the Kinect2 SDK. Several of these features are also immediately relevant for the mobility aspects of OaM training, supplemented by the feature foot lift.

Further, the analysis of cane moving technique in OaM can be based on that one of crutches in orthopedic rehabilitation. In both applications, the relation of the patient's steps (or ankle points) has to be analysed in relation to the cane tip (crutch tips respectively). Similarly, methods already used to analyse the upper body posture can also be transferred to OaM training and extended to head and hand posture, too.

Furthermore, a good observability of the gait exercises is of great importance in both rehabilitation contexts. Thus, the robotic methods on maintaining a defined distance between the robot and the patient by driving ahead [3] or by driving behind [17] should also be transferred in the ophthalmological application. The same applies to the implementation of an approaching persons' behavior [17], in the ophthalmological context to establish suitable observation positions, e.g. to observe stair-climbing exercises.

Thus, it can be expected that both the used sensors and the methods to analyse gait characteristics already used in orthopedic rehabilitation context, can also be utilized for the planned ophthalmological application.

C. Selected Use Cases

From the considerations in the previous sections, various use cases can be derived that could be probably usefully implemented in a robot-assisted OaM self-training. This concerns the training of different kinds of cane usage and holding techniques, the training of a correct upper body and head posture, the training of indoor exploration strategies in a parkour with objects to be recognized, and the training of stair climbing on a training staircase.

From the set of these possible use cases, the sliding pendulum cane technique with correct working posture and the training of a correct upper body are considered as the two use cases for the first feasibility study in this paper. Therefore, the extraction of the positions of the cane depending on the position of the feet, the hand, the shoulders, the pelvis and the head are necessary. The position of the robot or the experimental platform for the feasibility study in relation to the patient has only to satisfy the observability of the features to be extracted.

IV. FEASABILITY STUDY

A. Experimental Setup

In our previous robot-assisted orthopedic and neurological rehabilitation applications, we used the robotic platform shown in figure 2 right (for a detailed explanation of this platform see [4]). Before using this platform for the new OaM application, a technically simplified experimental setup with the same main sensors was used (see figure 2 left).

These sensors are a laser range finder to detect distances and reflectance values of persons (their legs) and objects in the sensory detection range. Further, the Kinect Azure as an RGB-D depth camera is used to capture a depth image of the environment, detect persons, and extract a body skeleton via the corresponding SDK. The spatial arrangement of the sensors roughly corresponds to the height of the sensors integrated in the robot. Furthermore, the experimental set-up was designed to be movable to allow recordings of the moving patient at defined distances.

In the following sections, the data obtained from the laser and the RGB-D depth camera and the extracted features are presented. The evaluation of the obtained features with regard to the correct execution of the sliding technique with working posture is presented in section IV-C. Investigations of suitable feedback strategies to the visually impaired or blind patients require at least functional tests with users which were not yet carried out in this feasibility study. First ideas for this are presented in section V.

B. Sensor Data and Feature Extraction

Based on the two use cases i) sliding technique in working posture and ii) training of a correct upper body pose described in section III-C, in this section the sensor data and feature extraction approaches required for these use cases will be discussed. All subsequent investigations were carried out with regard to observability of the person by the experimental setup from behind, from in front of and from the side as well as at different distances of 1.8-5.0 m.

1) Detection of the position of the legs: From the *laser*, data of distance and reflection values (represent the amount of emitted to reflected light from when targeting an object) can be obtained. Only an angle of 120° from the frontal detection area of the laser was used by the assumption that the later used mobile robot's navigation behavior will keep the user central in the sensor system. As for the example of a distance of 2.2 m depicted in figure 3, the person's legs can be constantly detected and are distinguishable from other objects in all three directions of observation. Based on the xy position of the laser values (depicted in figure 3 last row), the legs of the frontal and the back view could be modeled by e.g. a parabola model for each leg and be tracked over time afterwards, as suggested in [18]. It should be noted that the laser is mounted at a height of 0.3 m and, therefore, the legs are detected at this height.

Using the *skeleton* obtained from the *Kinect SDK*, the ankle positions can be used to determine the position of the legs respectively feet. The studies in [13] demonstrated sufficient accuracy of the Kinect data compared to a Vicon system for patients with forearm crutches, where a standard derivation of the error of 4 cm was determined. Here, a further comparison of the accuracies of the skeleton data obtained from the RGB-D camera while observing a person using a cane and without a cane respectively were conducted. Comparing the histograms of the ankle joints of the skeleton at a typically distance of 2.2 m when using vs. not using a cane, it was found that the accuracy of the ankle positions is much lower when using a cane (about 3 cm difference in the average values). In the side view of the person the accuracy of the foot and knee joints was even lower due to the overlapping by the person's own body.

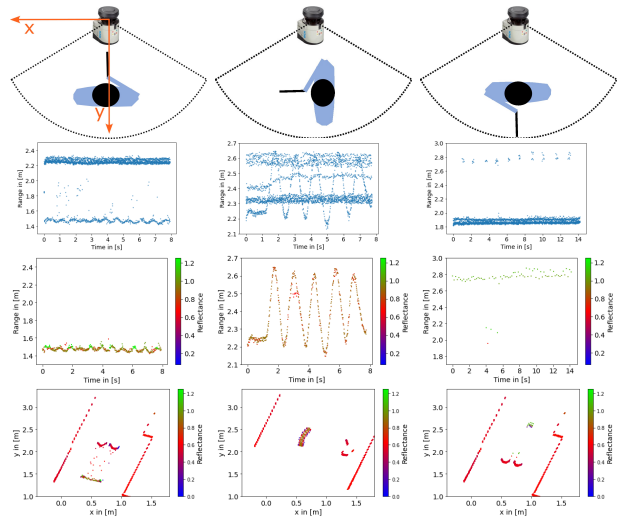

Fig. 3. The **upper row** of the images schematically show the recording pose of the person to the laser as well as its opening angle of 120°. The orientation of the person is towards (**left column**), parallel (**middle column**) and away from (**right column**) the laser. During the data capturing, the person was standing in a distance of 2.2 m over a period of around 15 s and was moving the cane to each side five times. The **second row** shows the distance and the **third row** the reflectance values (over a threshold) obtained. The **last row** depicts the xy position of the reflectance values while moving the cane one time.

2) Position of the cane tip: The refectance values of the laser can be used to detect the cane. In figure 3 (third row), by using a threshold of 0.66 applied to distinguish cane from legs, only the reflectance values of the cane remain. To view the person from behind (column right) seems less suitable, even if the swing arc width is correct. Only if the cane appears beside the legs the reflection values can be detected by the laser. However, if uniformity of movement is to be considered, there is not enough sensor data available. It should also be noted that the cane is detected by the laser at its height of 0.3 m. Therefore the cane tip itself can not be captured by the laser and is approximately 0.3 m more distant from the person located. Using the *RGB-D camera* alternatively, both the cane and its tip could also be determined (see figure 4).

3) Position of the hand: As described in section III-A, the hand must be immobile in front of the body in working position. The correct position can be evaluated by analysing the respective skeleton joint of right or left hand wrist.

Analysing the histogram of the hand joint for the cane holding right hand of the skeleton at a typically distance of 2.2 m, a standard derivation of 1 cm was achieved, which is high enough for evaluating the hand position. The same goes for the side view, provided the person is observed from the side in which the person holds the cane. Since the measurement accuracy decreases with increasing distance, it is necessary to ensure a measurement distance of 1.8-2.4 m,

what will be possible due to the human-centered guiding behavior of the robot as described in [17].

Fig. 4. Depth image of the Kinect Azure showing that the depth values for the cane differ significantly from these of the person or the background. Converting the depth image to a point cloud, it is expected that the cane can be detected by the RANSAC algorithm [19] used for forearm crutch detection [13]. This will be investigated as part of the implementation of the method for feature extraction on the robot.

4) Position of upper body and head: As described in section III-A, the person has to walk upright with a non-moving head. To evaluate this, the respective angles between the joints of pelvis and neck (for the tilt of the trunk, see figure 7 below), those for neck, left and right ear (for the tilt of the head, see figure 7 middle) and those for nose, left and right ear (for the rotation, see figure 7 top) have to be extracted from the skeleton. The shoulder joints are needed to analyse the correct width of the cane movement. To determine the real shoulder width, both shoulder joints of the skeleton require an offset of approx. $5\,\mathrm{cm}$.

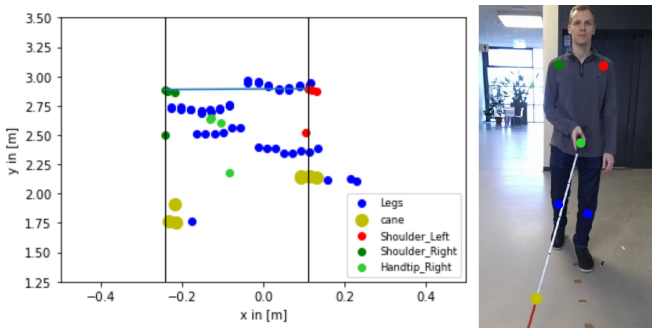

Fig. 5. In this figure, a step of about $60\,\mathrm{cm}$ with the left leg is visible. The walking direction is towards the sensors (to lower y-distance values). **Left:** Extracted features from laser data of legs and cane, as well as from skeleton joints of shoulders and cane holding hand. While sliding, the cane should cover the area in front of the legs and beside the shoulders. Because of the position of the laser in a height of $0.3\,\mathrm{m}$ the depicted cane position is obtained from the same height. Therefore, the cane tip is to be expected approx. $5\,\mathrm{cm}$ more left or right respectively. A more accurate position of the cane tip will be achieved by analysing the depth image of the RGB-D camera (see figure 4). In addition, the real shoulder width is approx. $10\,\mathrm{cm}$ larger than the depicted green line between the shoulder joints. The visualized movement of the right leg results from the tilting movement of this leg with standing foot during the step with the left leg. This and the misdetections of both legs show the need to use further pre-processing of the laser data for the legs, e.g. by a tracking system, as in [20]. **Right:** RGB image of the situation after the person has taken a step with the left foot and deflected cane from left to right. The extracted features are also shown schematically in the RGB image.

A subset of the discussed features was fusioned in a common coordinate system (see figure 5). There, the position of the cane (depicted in yellow) and the position of the feet (depicted in blue), both extracted from laser data are shown for one step in frontal view. The corresponding positions of the shoulder joints (depicted in red and dark green), and the position of the hand joint (depicted in light green), extracted from the skeleton are also integrated.

C. Evaluation of the Use Cases

This feasibility study was carried out with one person. Based on the feasibility proof of the methods presented, an implementation on a mobile robot together with an automated evaluation is planned. This allows user tests to be conducted with people with different visual impairments. Based on the considerations in section III-C, the analysis of the relation between the features in figure 5 should allow the evaluation of the sliding pendulum technique in working position. First, the correct deflection of the cane regarding the shoulder's width is evaluated, where a healthy person introduced to the use of a cane, walked for approximately $2.5\,\mathrm{m}$ (four deviations of the cane to each side) behind the manually moved experimental setup in a distance of approximately $2.2\,\mathrm{m}$ (see figure 6). The distance of the shoulder joints of the person in this experiment was $35\,\mathrm{cm}$ (measured over all skeleton data of this person) with a real shoulder width of $45\,\mathrm{cm}$. If performing a correct cane movement, the max. and min. deflection values should reach $0.21\,\mathrm{m}$ for the left side and $-0.21\,\mathrm{m}$ for the right side respectively (shoulder width plus $3\,\mathrm{cm}$ and taking into account that the cane was measured in a height of $30\,\mathrm{cm}$).

In figure 6 (left), although a mean value of $0\,\mathrm{cm}$ was expected for the deflection, the mean value in this experiment was $1\,\mathrm{cm}$. The reason for this was that the perspective from which the experimental setup was observing the person changed at the beginning due to inaccurate moving, which caused the curve to shift. Applying a PCA of theses data firstly should be useful and will be done for future data analysis. By assessing only succeeding deflections, a deflection of the cane to the left side (black vertical line) was almost correct but the deflection to the right side seems not enough.

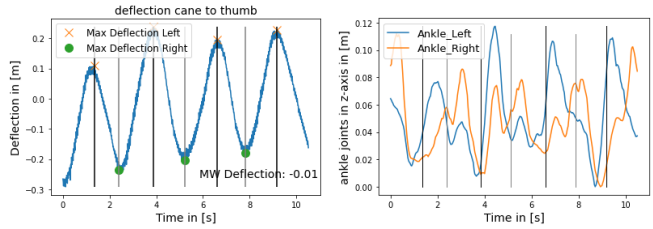

Fig. 6. **Left:** The blue line shows the deflection of the cane at its distance (in a height of $30\,\mathrm{cm}$) to the thumb joint. The vertical lines indicate a maximum deflection of the cane to the left (black vertical line) and to the right (grey vertical line) respectively. **Right:** The change from a grey to a black vertical line corresponds to the movement of the cane from right to left, accompanied by taking a step with the right foot (raising and declining of the orange line). The same applies to a step with the left foot (raising and declining of the orange line) and the deflection of the cane to the right (grey vertical line).

In figure 6 (right), the heights of the ankle joints of both legs (as a measure of a step) in relation to the deflection of the cane are depicted. Each local maximum of the orange line represents a lifting and setting down of the right foot

and the blue line represents the left foot respectively. There, the rhythm of putting a step with the right foot while moving the cane to the left and moving it back while putting a step with the left foot can be seen. The ankle joints from the skeleton were used despite of their determined inaccuracy (local maxima for ankle heights in figure 6 right) until a laser-based foot tracking system yielding more accurate values will be available for this work.

Furthermore, the stability of the position of the cane holding hand was determined by analysing the hand joint over time, where a maximum standard deviation of $1\,\mathrm{cm}$ was determined. This can be interpreted as a stable hand posture.

For the use case *correct upper body pose*, data of the inclination of the trunk as well as of the rotation and the tilt of the head are depicted in figure 7. Before evaluating these angles and time course, therapists have to determine the thresholds to distinguish values to be corrected by feedback to the patient. In figure 7, the trunk angle of $3°$ indicates a low inclination of the person. Furthermore, the mean value of $7°$ of the rotation and the tilt angles indicate that the person's head was slightly tilted and the person looked preferred to the right. Also the standard deviations of the rotation ($2.3°$) and the tilt ($1.7°$) angles indicate a lower accuracy of the used head joints which are used for the estimation of the trunk tilt angle (standard deviation of $1°$).

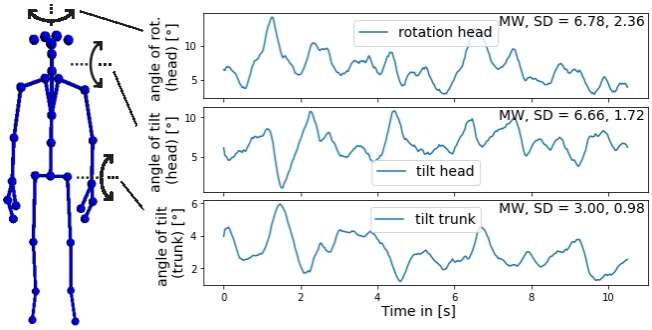

Fig. 7. Time courses of angles of head rotation (top), head tilt (mid.) and trunk tilt (below) determined of skeleton joints to evaluate the body posture.

V. CONCLUSIONS AND OUTLOOK

It was shown that it is possible to observe persons during OaM exercises with a simple 2D laser scanner and a RGB-D camera and to determine deviations from the intended behavior during the exercises with the necessary accuracy. Thus, the prerequisites are given to implement these techniques on a mobile robot in a next step and to make exercises possible that require patient-centered mobility. Further, rehab teachers need to define thresholds for the data required to evaluate the use cases, e.g. the minimum and maximum limits of cane deflection. Therefore, ground truth data guided or executed by a rehab teacher have to be captured. Since all gait analysis methods used are online-capable and gait errors can be determined in real time, immediate training feedback can also be given to the person exercising. Immediate feedback should be realised mainly via acoustic signals or acoustic clock generator. Using these sensors on a mobile robot together with the necessary human-centered navigation behaviours, user tests including blind and visually impaired persons are planned under clinic conditions and build a prerequisit for robot-assisted self-training of patients. Further feasibility approaches will be done for aspects of OaM like stair climbing. So, the robot is planned to assist the patients in self-training of exercises specified by the rehab teachers as the rehab teacher remains the leader of the training. Aspects of indoor exploration or gaze direction training are scheduled for later studies on the basis of an existing stable robotic application.

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