Making Gait Training Mobile - A Feasibility Analysis*

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***Abstract*— As a part of a feasibility analysis, this paper reports that gait analysis of orthopedic-surgically treated patients is possible by using a *Kinect v2* sensor as a low cost depth camera instead of applying a conventional marker-based multi-camera system in a gait laboratory. Being aware of the strengths and weaknesses of this approach, our concept expands the potential of gait analysis from diagnostic use only toward the use for documented and actively corrective self-training of patients. The paper analyzes which gait parameters are needed for synthetic, but effective gait evaluation, and if it is possible to obtain them from the *Kinect SDK* skeleton in terms of exact and stable values compared to parameters obtained by a multi-camera system in a gait laboratory. The main contributions of this paper are the analysis of the usability of the *Kinect v2* for mobile gait analysis.**

I. Motivation

As motor learning is not a passive process, patients recovering from an orthopedic-surgically treatment must play an active role in the rehabilitation process if improvement is to occur. Against this background, a new trend in rehabilitation care is promising vast medical as well as economic potential - the so-called self-training of patients, Andrade [1] have already dealt with the topic in stroke patients. Further, therapists have to do hands-on therapy mainly, so repetitive training is in the responsibility of the patients themselves. Also gait training in a gait laboratory is rather suitable for diagnostic use than for a frequent training due to the huge effort to attach the infrared markers to the patients. An example for a self-training system was already demonstrated in the research project ROREAS [2], [3] running from mid 2013 till spring 2016, which aimed at developing a robotic rehabilitation assistant for walking and orientation self-training of stroke patients in late stages of the clinical post-stroke rehabilitation. The robotic rehabilitation assistant was to accompany selected patients during their walking and orientation exercises, practicing both mobility and spatial orientation skills.

Key importance to a successful gait self-training is the prompt detection of gait errors and also to immediately give corrective feedback to the patient, so that gait errors once made do not influence the patients gait durably [4]. For this reason, a feasibility analysis using the skeleton of the *Kinect SDK* was carried out as a cost-effective alternative to expensive multi-camera systems. As an advantage, the *Kinect v2* can also be integrated in autonomous robots, enabling a truly mobile self-training and represents the overall goal of our research group. In collaboration with the Waldkliniken Eisenberg (Germany), relevant parameters for evaluating the gait were worked out.

In order to get closer to the goal of mobile gait analysis (see Sec. IV), a test setup with a static *Kinect v2* was carried out in Sec. III. The aim was to determine an optimal camera height, a suitable camera angle to the walking path and the distance to the camera for reliable detection. In addition, results could be achieved without additional errors due to robot movements and finally compared with the laboratory system (*Vicon*). Sec. IV finally contains a first test of a mobile robot for gait analysis. The data previously obtained from the static test are used as comparative data. At last Sec. V gives an outlook on next steps for the gait training using a mobile robot.

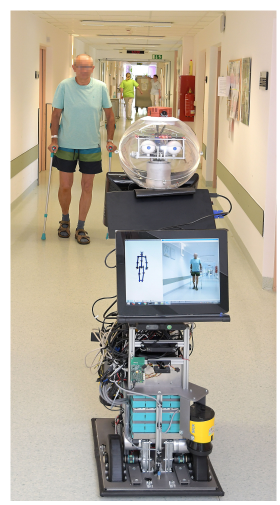

Fig. 1. Robotic training companion during gait training.

II. Related Work

In previous works [5], [6] and [7] an alternative to expensive laboratory systems is shown. They arranged the *Kinect v2* sensor statically in a laboratory environment or on a treadmill, evaluating temporal parameters and joint angles.

A mobile variant of the gait analysis using the *Kinect v2* was developed in a previous study [8]. A six-wheeled robot drove in front of the subject and evaluated parameters such as walking speed and step length. Martins et al. [9] developed

*This work has received funding from the Thuringian Ministry for Economic Affairs, Science and Digital Society (TMWWDG) to the project ROGER (grant agreement no. 2015 FE 9088).

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a smart walker, which detects the legs using laser sensors and thus records motion trajectories. On the basis of these trajectories, various parameters are extracted and evaluated.

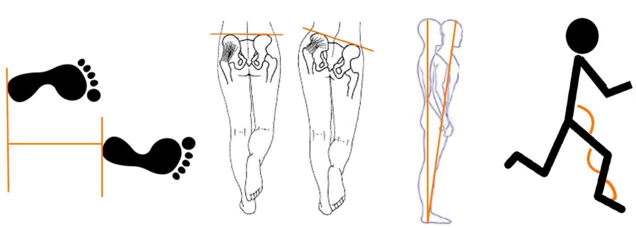
In all cases the temporal results of the *Kinect v2* were well in agreement with the reference system. The *Kinect v2* also achieved good reults at the joint angles, but it was noticeable that the estimation of the skeletal points in the foot area is very inaccurate and therefore, for example, angles to the ankle joint pose a problem.

However, none of these approaches presents a mobile system that, without additional appliances used by the test persons, can determine both time distance parameters and joint angles. However, the aim was not to correct the subjects immediately, but only to compare the *Kinect* with the respective reference data.

III. Investigation of the Static Setting

A. Abnormal gait pattern of a human after total hip arthroplasty

After a hip prosthesis surgery, errors in the gait pattern may occur in order to avoid pain, insecurity or lack of mobility in the lower extremities. Therefore, these errors can be detected using simple spatio-temporal parameters. In [10], [11], [12] *Cadence*, *Walking Speed*, and *Step Length* play an important role, this parameters are defined as follows: *Cadence* is the number of steps per minute and is 100 - 130 $\frac{steps}{min}$ for a normal gait pattern. *Walking Speed* can be used to assess how many meters a patient can cover within one minute. Normally, this value is 82 - 84 $\frac{m}{min}$. *Step Length* is defined as the distance between the ground contact points of the two feet, as shown in Fig. 2. Usually it is between 0.65 m and 0.75 m. These parameters can be significantly smaller after an operation and a patient could also have an asymmetrical *Step Length*. In addition, periods of ground contact with one foot (*Single Support Left/Right*) or with both feet (*Double Support Left-to-Right/Right-to-Left*) can provide information on the gait pattern. The *Double Support* phase becomes longer at the expense of *Single Support* of the operated leg to avoid pain or even insecurity.



(a) (b) (c) (d)

Fig. 2. Definition of (a) *Step Length*[1], (b) *Pelvic Drop*[2], (c) *Lean Trunk*[3] and (d) *Flexion/Extension* of hip, knee and ankle.

Besides these simple spatio-temporal parameters, the temporal characteristics of different joint angles can be of interest according to Götz-Neumann [10]. This includes flexion/extension in the ankles, knees, and the hip as well as the tilt of the pelvis (*Pelvic Drop*) and the forward/backward lean of the trunk (*Lean Trunk*), as shown in Fig. 2.

In combination, all these parameters provide information on evasive movements.

They are tested for their recognition reliability with a *Kinect v2* in the following.

B. Subjects and Experimental Setup

The initial measurement in the static setup with the *Bonita* and *Kinect v2* was performed on 3 subjects (2 male, 1 female, 2 healthy and 1 with treated hip dysplasia). Each subject ran along the walking path in the gait laboratory ten times.

A 3D motion analysis laboratory system (*Vicon*) with 10 infrared cameras (*Bonita 10*) was used to generate the ground truth. Moreover, data were recorded with the *Kinect v2* which was positioned at different heights (100 cm, 120 cm, 150 cm) and angles (0°, 10°, 20°) to a defined walking path within the laboratory system, for testing the skeleton robustness. Infrared markers for the laboratory system were placed on each participant according to the *Plug-in-Gait* model[4]. In this model, only the lower part of the body and two markers on the upper body (left and right shoulder, see Fig. 3) were used. In Fig. 4 sample skeletons of the *Kinect v2* and *Bonita 10* are shown. For data synchronization, the *Kinect v2* sensor is also tagged with four markers (see Fig. 3).

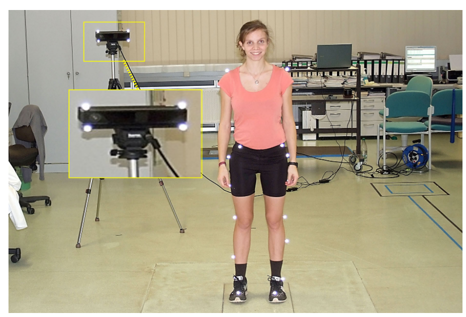
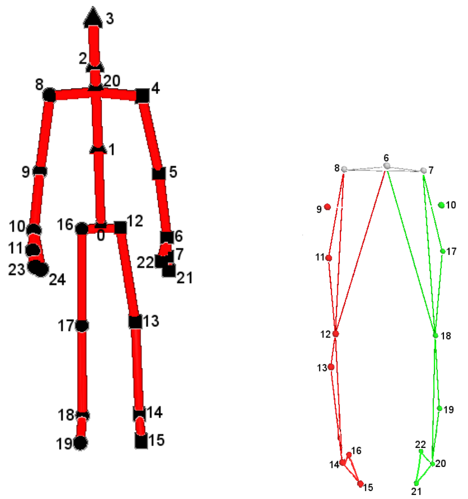


Fig. 3. Marker placement of the partial *Plug-in-Gait* model on the lead author. Only the lower body and the markers on the shoulders were used for the test. The infrared markers on the *Kinect v2* sensor are used to identify its position in the laboratory system.

C. Experimental Procedures

A spatial synchronization is necessary for comparability of the both camera systems' results. Therefore, the infrared

[1] https://www.flaticon.com/free-icon/footprint_25193
[2] http://www.qucosa.de/fileadmin/data/qucosa/documents/4232/data/kap3.html
[3] https://d2gg9evh47fn9z.cloudfront.net/thumb_COLOURBOX6321873.jpg
[4] http://www.idmil.org/mocap/Plug-in-Gait+Marker+Placement.pdf



(a) (b)

Fig. 4. Illustration of the skeletons for different camera systems. (a) shows the *Kinect v2* skeleton, (b) shows the *Bonita 10* skeleton, but only the lower body (shoulder markers are missing).

markers on the *Kinect v2* were used, which provide information about the displacement and rotation of the *Kinect v2* with respect to the laboratory system's point of origin (see Fig. 5).

In addition to the spatial synchronization of the systems, temporal synchronization is necessary as well. At the beginning of each recording the test persons moved into the recording area and did a squat. In doing so, the timestamp of the lowest point of the sacrum marker (*SACR* (Fig. 4b, joint 6) or *SpineBase* (Fig. 4a, joint 0)) served as a synchronization point. Afterwards, they moved backwards out of the area and then completed the entire walking path in their usual walking style. For the *Kinect v2*, only the data points which were not more than 4 m away from the sensor were used since otherwise a robust estimation of the skeletal points could not be guaranteed.

After successful synchronization, the data points of the two ankle joints are used to define the double steps. One double step is defined as the time span one ankle joint needs to pass the other twice during consecutive swing phases. For the steps detected in the *Kinect v2* data, the laboratory system's data from the same time interval are also stored.

D. Results for the Static Setting

During the tests to see if the *Kinect v2* could provide comparable results to the laboratory system, problems arose with a camera angle of 10° and 20° between the optical axis and the walking path. Due to occlusions resulting in an incorrect estimation of the skeleton points, there are problems with the skeleton's detection accuracy using the *Kinect v2*.

For this reason, only a camera angle of 0° has been taken into account in the following evaluation.

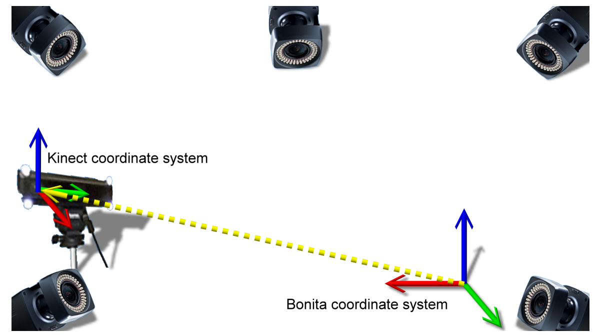


Fig. 5. Visualization of the spatial synchronization. yellow: desired transformation.

1) Spatio-temporal Analysis: In Table I the mean value and standard deviation of the error between the two recording systems (laboratory system and *Kinect v2*) are listed.

The values in this table show that the error between the two systems is low. Our spatio-temporal results and those presented by Elthoukhy et. al [7] and Clark et al [13] were comparable (see Table I). These preliminary results suggest that the *Kinect v2* might be a suitable tool for the analysis of spatio-temporal parameters that characterize gait.

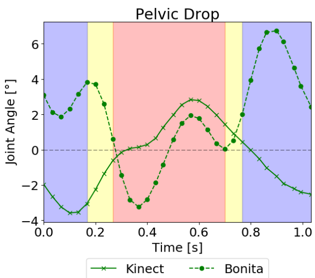
TABLE I. Summary of the mean error (standard deviation) between the two camera systems for all subjects and the mean value (*Kinect v2*) (frontal view with 0°, height: 120 cm).

	mean value	**mean error (std)**	
Cadence [steps/min]	114.62	1.532 (1.0355)	spatio-temporal
Walking Speed [m/s]	1.49	0.029 (0.0132)	
Step Length left [m]	78.31	0.032 (0.0178)	
Step Length right [m]	77.97	0.035 (0.0257)	
Strid Time [s]	1.05	0.014 (0.009)	
Single Support left [s]		0.031 (0.0284)	
Double Support left to right [s]		0.021 (0.0225)	
Single Support right [s]		0.020 (0.0192)	
Double Support right to left [s]		0.018 (0.0296)	
Pelvic Drop [°]		4.105 (2.4332)	joint angles
Forward/Backward LeanTrunk [°]		0.805 (0.5539)	
Flexion left knee [°]		4.425 (3.4019)	
Flexion right knee [°]		5.313 (4.1931)	
Rotation left feet [°]		13.026 (13.9499)	
Rotation right feet [°]		14.645 (19.5169)	
Rotation left feet (Stand) [°]		7.210 (7.0766)	
Rotation right feet (Stand) [°]		8.183 (7.1415)	

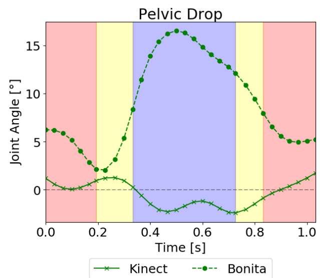
2) Kinematic Analysis: Considering *Pelvic Drop*'s average error between the camera systems (4.105°) and its standard deviation (2.433°) over all subjects at a frontal recording position, this indicates a small difference. If the temporal characteristics are considered, there are clear differences between the two camera systems, which are confirmed by the qualitative comparison in Fig. 6.

With an error of 4.425° for the left knee and 5.313° for the right knee in the same data (see Table I), a small error between both systems can be observed. When looking at the graph in Fig. 7, a similar course of the two camera systems can be recognized. The spike in the bonita's line of the left

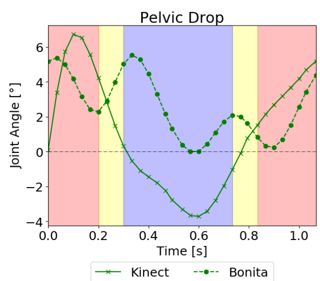
IEEE Int. Conf. on Biomedical Robotics and Biomechatronics (Biorob), Enschede, The Netherlands, pp. 484-490, IEEE 2018



(a) *Prob01*



(b) *Prob02*



(c) *Prob03*

Fig. 6. Exemplary temporal characteristics for one double step of *Pelvic Drop*. (a) shows the characteristics for *Prob01*, (b) for *Prob02* und (c) for *Prob03*. The different colors in the graph represent the individual support phases. red: Single-Support left, blue: Single-Support right, yellow: Double-Support

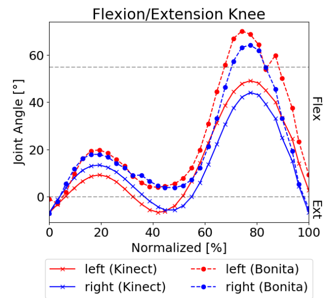
Knee suggests a problem in the tracking procedure. Perhaps there was an occultation caused by the Kinect or the patient himself.

The mean error and its standard deviation between the two systems for the lean of the trunk (*Lean Trunk*) show that the values of the laboratory system and the *Kinect v2* are also very similar. The error between both systems is very small at only 0.805°. The graphs in Fig. 8 show a similar course of the curves for all subjects.

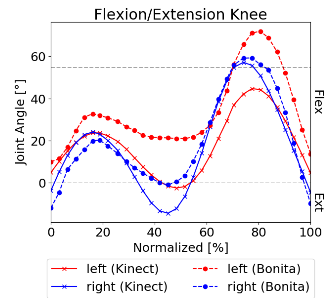
In Table I, the error and the standard deviation of the rotation of the feet between the two systems are shown for the complete gait cycle and also for the standing phase only. In both cases, there is a large error, though in the standing phases the error is about half as large as for the complete cycle. Due to the uncertain detection of the forefoot, this parameter cannot be satisfactory be evaluated.

E. Conclusion regarding the choice of gait parameters

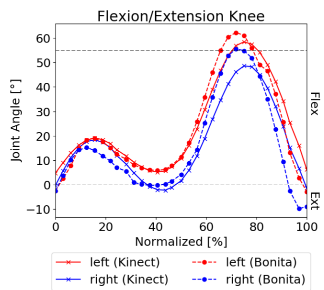
Generally, the error between the results of the *Kinect v2* sensor and the results of the laboratory system is, according to the clinic staff, within acceptable boundaries, allowing the spatio-temporal parameters to be analyzed autonomously in a static experimental setup using the *Kinect v2*. The analysis of the *Support Phases* is also possible with a static *Kinect v2*. The left and right phases should be symmetrically for a normal gait. The analysis of the joint angles, however, causes problems. Especially the *Pelvic Drop* cannot be analyzed with the *Kinect v2* due to the fact that the joints at the pelvis



(a) *Prob01*

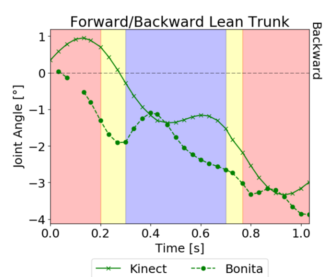


(b) *Prob02*

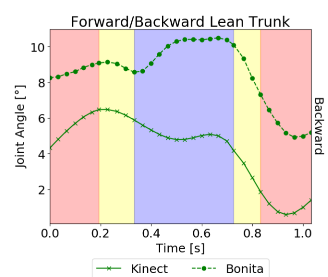


(c) *Prob03*

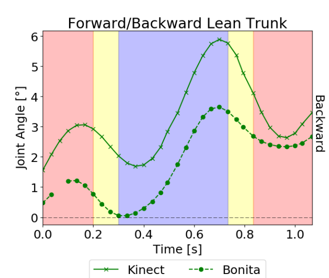
Fig. 7. Temporal characteristics of *Flexion/Extension Knee* over time for all double steps of one subject. (a) shows the characteristics for *Prob01*, (b) for *Prob02* and (c) for *Prob03*. The horizontal dashed line marks 55° flexion, which must be reached in the swing phase for sufficient ground clearance.



(a) *Prob01*



(b) *Prob02*



(c) *Prob03*

Fig. 8. Exemplary temporal characteristics for one double step of *Forward/Backward Lean Trunk*. (a) shows the characteristics for *Prob01*, (b) for *Prob02* and (c) for *Prob03*. red: Single-Support left, blue: Single-Support right, yellow: Double-Support

are always estimated vertically aligned in the model of the *Kinect SDK*, since the person is assumed to be healthy. For controlling video games, which the *Kinect v2* was developed for, the tilting of the pelvis plays a minor part, so that this does not have to be taken into account there. However, this has the consequence that this clinically relevant parameter cannot be evaluated autonomously with the *Kinect SDK* during gait training. Furthermore, the rotation of the foot is an indication for the position of the hip, but this parameter cannot be evaluated reliably as well. This is mainly due to the uncertain estimation of the forefoot marker. Due to the unsafe detection, the joint angle's position changes rapidly, and it is not possible to make a trustworthy statement on this parameter. A further indication of a changed gait pattern is the posture of the upper body. If the position is not upright, it can be assumed that the patient makes evasive movements in order to relieve the operated side. The analysis of this parameter is possible considering the course of the curve and the errors between the systems, but further tests need to be carried out in this respect. In addition, a threshold value must be determined in consultation with therapists. Often after an operation, the affected leg is not lifted as far from the ground as the other leg which should be prevented as quickly as possible. The *Kinect SDK* makes it possible to evaluate this parameter by looking at the flexion of the knee. This flexion can be calculated relatively robust. The calculation on a hip dysplasia patient is strongly influenced by the incorrect estimation of the hip markers. The extent to which autonomous analysis is possible should be evaluated by further robustness tests.

IV. Investigation of the Dynamic Setting

A. Technical Devices

For the experiments in the dynamic setting, a mobile robot with a maximum speed of 1 $\frac{m}{s}$ based on the platform presented in [2] was used (see Fig. 9). It is equipped with two SICK S300 laser scanners, covering the full 360° area of the robot's environment for reliable localization and obstacle avoidance. In addition to this 2D sensor data, it utilizes two ASUS RGB-D cameras at the front for 3D obstacle detection at closer distances. The robot platform also has four head-mounted RGB cameras, giving it a complete all-around field of view, e.g. for visual person detection. As an extension to the platform in [2], a *Kinect v2* RGB-D sensor was mounted on a pan-tilt-unit (PTU), allowing the platform to keep a good view on the patient even during evasive navigation maneuvers. For details on the control algorithm of the PTU refer to [14].

B. Subjects and Experimental Setup

For tests on a mobile robot platform, the *Kinect v2* was mounted at a height of 85 cm. Two tests were carried out with the mobile setup. (A) Long ways on a corridor to simulate a training process, the goal was to find out the behavior and the limits of the robot and the *Kinect v2* over longer ways. (B) Short distances in the gait laboratory, this made it possible to generate reference data and to obtain better

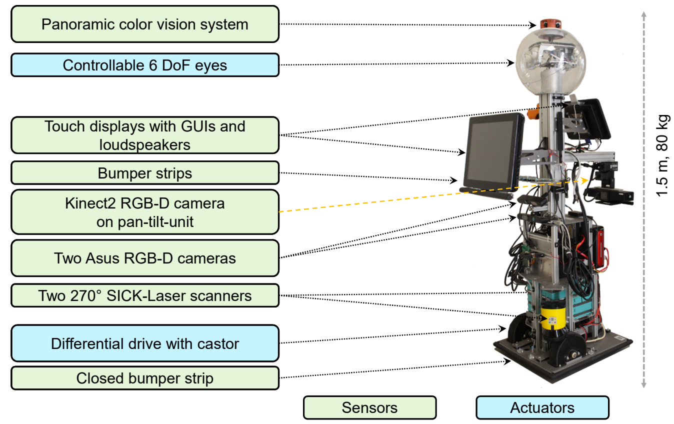


Fig. 9. Robot companion ROGER with its main equipment.

information regarding the accuracy of the *Kinect v2* in a mobile application scenario.

For test (A) the test track was a U-shaped track with a length of about 50 m. The robot moved as a guide in front of the subject. In order to ensure a reliable estimation of the skeleton, it was necessary that the test persons walked behind the robot as frontal as possible at a certain distance (in our case 2.50 m). In total, two of the test persons from the static test (1x male, 1x female) moved along the test track three times each. During the test run, the robot tried to keep the subjects in the middle of the camera image with the aid of its camera control [14]. The subjects were encouraged to follow the robot in the usual walking style. Since bends were included in the experiment's track, areas with straight path sections must be identified to ensure correct calculation of the parameters. Fig. 10 serves as an illustration. The double step extraction then took place as defined in the static setup.

In test (B) patients with an operated hip prosthesis were running, so that data could be collected from the laboratory system and the *Kinect v2*. Altogether in the gait laboratory 12 patients (7 male, 5 female) walked ten times a distance of about 6 m. In the gait laboratory, the patient only walked straight ahead and no further pre-processing for extraction of the double step was necessary.

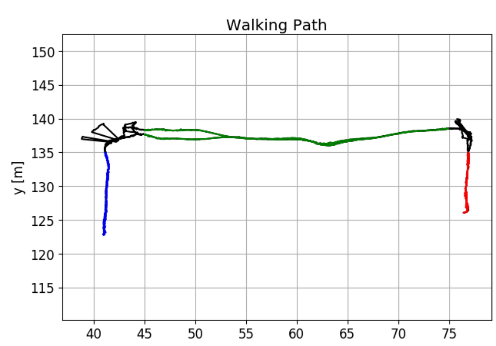


Fig. 10. Illustration of the different computation areas. black: not included, red, blue: positive/negative y-running direction, green: positive/negative x-running direction

C. Results using a Mobile Robot

1) Spatio-temporal Analysis: Since no laboratory system is present in the U-shaped track so far, the analysis of the spatio-temporal parameters had to be limited to an assessment of the results' consistency within the dynamic test itself. One of the most important results is that the participants automatically adapted their gait patterns during the slow maximum speed of the robot (1 $\frac{m}{s}$) and the desired distance the test persons have to keep for a robust estimation of the skeleton strongly influence the spatio-temporal parameters. This leads to a stroll and influences both spatio-temporal parameters and the joint angles. Mean and standard deviation are shown in Table II.

The standard deviations of the respective parameters provide information about the coherence of the results gained on the mobile system. Since none of the standard deviations has a large value, it can be inferred that the skeleton detection is also stable on a mobile platform.

TABLE II. Mean (standard deviation) of spatio-temporal parameters for the dynamic and static scenario. The results are shown for *Prob02* and *Prob03* at a camera height of 85ċm (dynamic setting on the robot) and 120ċm (static setting).

	Prob02		**Prob03**	
	dynamic	**static**	**dynamic**	**static**
Cadence [steps/min]	88.486 (3.4820)	114.688 (1.7659)	91.892 (3.8734)	112.530 (0.0566)
Walking Speed [m/s]	0.861 (0.0605)	1.495 (0.0191)	0.856 (0.0630)	1.359 (0.005)
Step Length left [m]	0.574 (0.0364)	0.753 (0.0257)	0.593 (0.0498)	0.764 (0.006)
Step Length right [m]	0.593 (0.0499)	0.812 (0.0164)	0.525 (0.0401)	0.686 (0.0082)

The duration of the four *Support Phases* also differ from those of the static test, while the distribution of the duration for the mobile system is minimal, too. The deviation between static and dynamic setup is also caused by the adjustment (the strolling) of the gait pattern. This also indicates a reliable recognition of these parameters. The results are shown in Table III.

TABLE III. Mean (standard deviation) of the durations of the different support phases for the dynamic setup. The results are shown for *Prob02* and *Prob03* at a camera height of 85 cm.

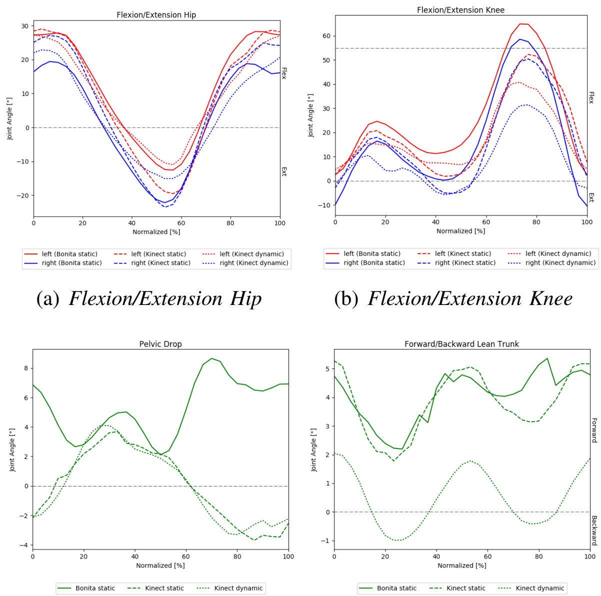
	Prob02	**Prob03**
Single Support left [s]	0.476 (0.0779)	0.475 (0.0635)
Double Support left to right [s]	0.187 (0.0828)	0.176 (0.0618)
Single Support right [s]	0.475 (0.0781)	0.512 (0.0573)
Double Support right to left [s]	0.220 (0.0804)	0.146 (0.0587)

The comparison of the mobile gait analysis (in the gait laboratory - Test (B)) was first made on the step length, as this already looked promising in the static test (see Sec. III). In Table IV the mean value and standard deviation for the step length are shown. Patients 02 and 05 are given as examples for typical gait errors after a hip operation due to incorrect loads. It is easy to see that operation-related step length deviations are not only detected by the laboratory system, but also by the *Kinect v2*. In patient 02, the right side is operated , which is well reflected in the data, as the step length for the left leg is only 29 cm, while the step length for the right side is 52.8 cm. In patient 05, the left side is operated, and also here a difference of 10 cm can bee seen between the right and left leg (see Table IV).

TABLE IV. Mean value (standard deviation) of the step length in [cm] for the dynamic setup in the gait laboratory for the *Bonita* (laboratory system) and *Kinect v2* are shown. In three test subjects (2male, 1 female) the evaluation caused problems, so that they were not considered further at first.

Pat.	***Bonita* (laboratory)**		***Kinect v2***	
	left	**right**	**left**	**right**
01	55.0 (2.6)	54.4 (1.5)	49.7 (2.6)	40.0 (6.8)
02	29.0 (2.9)	52.8 (3.2)	29.7 (4.5)	50.0 (4.8)
03	60.2 (4.9)	60.1 (8.6)	63.8 (11.2)	59.3 (13.1)
04	41.8 (4.3)	38.8 (3.2)	39.5 (6.6)	38.5 (3.9)
05	51.1 (1.3)	41.7 (2.0)	49.0 (7.7)	34.9 (12.0)
06	52.6 (3.1)	40.2 (4.1)	47.8 (33.7)	40.8 (40.5)
07	56.4 (3.2)	58.9 (2.9)	51.9 (4.6)	61.0 (3.4)
08	54.7 (1.6)	62.7 (3.0)	56.6 (7.9)	56.0 (15.2)
12	42.3 (21.5)	60.4 (6.8)	37.2 (20.1)	59.0 (16.5)

2) Kinematic Analysis: Most of the characteristics of the joint angles depend less on the walking speed, so that the adaptation of the gait pattern caused by the robot's guide behavior has a negligible impact. Thus in Test (A), the reference data of the laboratory system from the static test can be used to evaluate the joint angles. To achieve this, the time base of the double step is converted from absolute values (seconds) to relative proportions of the gait cycle's total duration to allow a comparison this way. Fig. 11 shows the averaged course of the different joint angles over all subjects. The error and standard deviation are shown in Table V. The courses for *Flexion/Extension Knee* and *Flexion/Extension Hip* correspond with the results of the static setup. However, the values for mobile *Kinect v2* are slightly lower. This is probably based on the patients' reduction in speed due to the low robot speed and the resulting stroll. The graphs for *Pelvic Drop* of the *Kinect v2* are almost identical. This illustrates the effect that the hip is estimated incorrectly by the *Kinect v2*. The difference to the laboratory system is much greater. The *Forward/Backward Lean Trunk* courses look quite similar, but can only be compared with each other in a poor way, since it cannot be guaranteed that the subject moved the upper body in the dynamic test as much as in the laboratory. This parameter can vary greatly from experiment to experiment, since it is influenced by external impacts, such as a communication partner walking together with the patient. It is not possible to make a statement about the *Rotation Feet* in this mobile system, too. The forefoot marker fluctuates in such a way in the dynamic data that it has been eliminated for a proper analysis of the data and, therefore, can no longer be used for evaluation.



(a) *Flexion/Extension Hip* (b) *Flexion/Extension Knee*

(c) *Pelvic Drop* (d) *Lean Trunk*

Fig. 11. The graphs compare the courses of the different joint angles for the averaged and temporally normalized double steps of the mobile test setup (dotted line) with the ones from the static setup. For the static setup, both the laboratory system (solid line) and the *Kinect v2* (dashed line) are shown. The left side is shown in red and the right side in blue.

TABLE V. The error (standard deviation) of the joint angles between mobile *Kinect v2* and the laboratory system as well as the *Kinect v2* from the static setup respectively. The values are averaged over all test persons.

Joint angles	mobile *Kinect v2* vs. static ***Bonita***	mobile *Kinect v2* vs. static ***Kinect v2***
Pelvic Drop	4.829 (3.7459)	0.666 (0.5161)
Flexion/Extension left Hip	2.838 (2.1967)	4.276 (2.3030)
Flexion/Extension left Knee	9.351 (7.1239)	5.189 (4.4721)
Flexion/Extension right Hip	3.581 (2.0561)	3.490 (1.9732)
Flexion/Extension right Knee	10.728 (8.5081)	7.779 (5.8393)
Lean Trunk	3.021 (0.9303)	3.055 (0.4910)

3) Conclusion: The consistency of the results is ensured in the mobile test setup. What can also be concluded, is that the robot probably moved too slowly for a gait analysis of healthy adults, and the speed would have to be increased so that the test persons do not have to adjust their walking speed. When looking at the averages of both setups (see Table II), it can be noticed that an adjustment of the gait pattern has occurred.

According to the hospital staff, the experiments in the Waldkliniken Eisenberg have shown values between 0.13 $\frac{m}{s}$ and 0.48 $\frac{m}{s}$ for a changed maximum speed due to an operation, so that nothing stands in the way of practical use from that point of view.

The results for the experiment in the gait laboratory (Test (B)) are approximately in the same range for the *Bonita* and the *Kinect v2*. Above all, it is easy to see the deviations in step length are also detected well by the *Kinect v2*. A detailed analysis of the significance is currently being carried out by physiotherapists and will be presented in future works (see Sec. V).

V. Future Work

Further tests for determination of threshold values for recognizing gait errors have to follow now based on the work presented here. In future work, physiotherapists will use video data and the *Bonita* and *Kinect v2* data to define limits for gait parameters more precisely. Most important is, however, the validation of the *Kinect v2* in the dynamic setup. Our research group is working on evaluating the other gait parameters in relation to the laboratory system. Furthermore there are ongoing works for a mobile robot scenario where our endeavor is to validate the presented approach in a corridor environment that is not confined to a relatively small gait laboratory.

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