Human Feet Tracking in Arranging the Navigation of a Robotic Rollator

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***Abstract*— This paper presents an indirect user interface solution for an active walking aid using visual image sensing. The aim of the design is to track the movement of the human feet in order to obtain command signals for driving an active walker to be seen as a robotic rollator. The human gait becomes the input device by which the user controls the actuators of the robotic rollator. Computer vision techniques are used to track the user's feet as end effectors during human gait. A camera is mounted on the frame of the rollator and captures video images of the user's feet. The kinematics of the feet are measured in two dimensions to obtain the position and orientation of the user's body. The measured motion parameters of the feet are relayed to the desired position and orientation of the rollator. The robotic rollator is to be used as a rehabilitation tool during everyday walking and gait training**

Keywords*— *human gait, feet kinematics, computer vision, robotic rollator

I. Introduction

The complex dynamic process of human locomotion involves the central nervous system, skeletal system and muscular system [1]. All these systems work together to allow and provide the progression, support and balance needed in the performance of activities of daily living [2]. Attacks on any of the systems due to injury, aging, disease or amputation result in impaired mobility. Mobility assistive devices have over the years helped combat mobility restrictions resulting from abnormal and pathological gait. From canes, wheelchairs to exoskeletons each mobility assistive device is chosen based on the extent of assistance needed by the user [3].

Walking aids are mostly used by the elderly and by persons with weak lower limb muscles to help provide support and balance during gait. Their major user requirement advantages are that they offer independency and promote physical activeness. Conventional walkers' gait cycles involve the user having to pick up the walker to move it forward and then follow by taking a step [4] which this tends to prevent a natural gait pattern. With the use of wheels, rollators make it easier for the user to move compared to standard ferruled walker. However, rollators require an effective breaking system as they have a propensity to easily slip off or roll away. For rehabilitation purposes as well as to allow travelling for longer distances over difficult terrains an active component is proposed.

Active or robotic walking aids have since been realised such as in [5]. Emerging at times with a similar structure as the rollators they explore motorised driving and human-machine interaction. The human-machine interfaces to robotic rollators are divided into two types, direct and indirect interfaces. For direct interfaces, the user controls the rollator by directly sending commands to the actuators. Indirect interfaces predict the user's intentions and in turn control the rollator.

The interaction configuration between the robotic rollator and user may be either autonomous or shared. Shared control can have the user perform cognitive decisive tasks and the rollator performing other functions. In autonomous control, the robotic rollator has full control over localisation, navigation or obstacle avoidance. This can be rather frustrating for the user and remove the feeling of independence, whereby the user is not in agreement with the decision taken by the rollator. Human in the loop may be used to balance the augmented level of a robotic rollator. Current research on exoskeletons employs human-in-the-loop control to assess the assistive device performance by using human physiological indicators such as muscle tension, pain and energy consumption to optimise the control of the device as can be seen in [6] [7]. Walking assistive devices such as exoskeletons [8] are quite costly and the user still needs crutches or a walker.

In previous work [9], the authors considered the use of indirect user interface for the robotic rollator using inertial sensor units (IMUs). IMUs mounted on each side of the upper left and right leg were used to track and measure gait parameters in order to determine the required command signals

978-1-5386-2775-4/17/$31.00 ©2017 IEEE

to drive the walking aid. Inertial sensors are compact, inexpensive and able to continuously track motions of the user's gait. The major disadvantage of the IMU sensors is that they have to be mounted on the user creating discomfort.

Visual image sensing method has been used to detect, record and study human motion [10]. Gait analysis with this method is usually performed in large specialised laboratories with expensive camera systems. Computer vision has made it possible to track human gait even in smaller settings as well as with inexpensive image acquisition devices. Computer vision applications in gait detection and analysis are studied in various research disciplines including clinical applications [11] and biometric technologies [12], [13]. This paper presents a non-contact visual sensing user interface solution for a robotic rollator. The user interface needs no cognitive ability as the user "unconsciously" controls the propulsion of the robotic rollator. The direct computer vision interface method minimises the gap between the user and the navigation control, whereby the rollator adapts to the user's gait.

II. Robotic Rollator Design

The design of the robotic rollator aims to cater as a general walking aid as well as for gait training purposes. The design further looks at aiding in trajectory of difficult uneven terrains and inclined trajectories. The robotic rollator can provide mobility assistance from either standing or seated position depending on the postural strength and ability of the user.

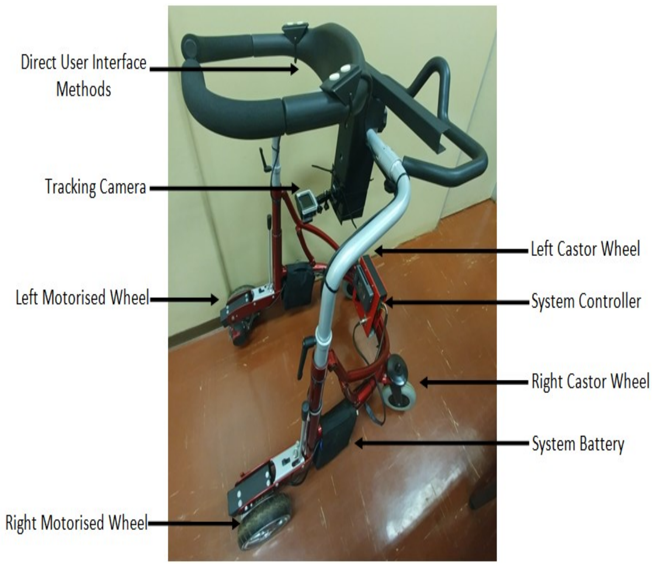

Fig. 1. Prototype design of the robotic rollator.

Fig. 1. shows the mechanical structure and major components associated with the robotic rollator design. The subunits of the rollator consist of the controller system, user interface systems and the actuator system. The rollator driving command can be determined by either user intent or measured progression of the user obtained by using the direct or indirect interface methods respectively. The direct user interface method requires the user to have cognitive ability in order to control the rollator, for example using pressure control buttons or a conventional joystick. A user who needs the rollator simply for extra support and balance during walking may use this method. The explored solutions for the indirect user interface method make use of IMUs [9] or a camera. For the indirect user interface, the user becomes an indirect controller of the robotic rollator. Navigation of the rollator makes use of the kinematic motion of the user. The measured user's kinematic motion parameters are processed and computed to determine the necessary control signals to be sent to the actuator system. In order to drive the robotic rollator accurately, a feedback control system will be implemented to compare the feedback signals derived from the sensors mounted on the actuators with the distance and velocity information of the user.

A. Design of the Visual Image User Interface

A camera together with the aid of National Instrument (NI) Labview vision assistant tool is used to acquire and track the feet of the user during gait. The camera is mounted on the frame of the rollator at about 0.7 m from the ground surface. The camera sensor is parallel to the plane of the feet motion. As the user walks, video images are captured at 25 FPS that is sufficient to acquire the user's gait motion. The planar real life image of the legs, camera distance and ground surface $R(X_i, Y_i, Z_i)$ is captured and projected into a planar camera two dimensional image $r(x_i, y_i)$.

The processing of the acquired images is performed using colour extraction, image calibration and machine vision functions of the NI vision assistive tool. The colour extraction plane is used to extract the luminance plane from the HSL image. This is to convert the images to 8-bit greyscale images for processing. Image calibration function uses point distance calibration to convert the pixel coordinates to real world coordinates based on a known distance. The system uses machine vision application pattern matching for the detection and tracking of the user's feet. A template for each left and right foot is created using the pattern matching function. From learning the template image of the foot, the application searches and compares the source image for patterns of pixels matching that of the foot template. Each foot is independently tracked and placed in a bounding box from one frame to next of the incoming video images. Pattern matching is chosen because of its independency to light, noise and change in orientation of the template of each foot.

III. Plane Measurement

This section discusses the measurement of linear displacement with internal and external axes rotations of the user's feet. The motion of the feet is examined and explained in a plane to get the required positions and orientation signals required for the motor commands.

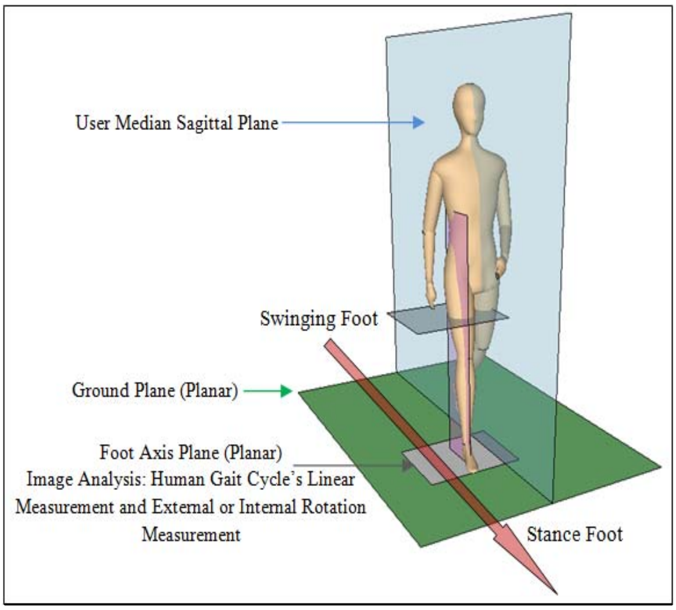

Fig. 2. Anatomical representation for measurement points.

The camera is positioned parallel to the ground plane in order to minimise the image's perspective distortion. The resulting scene taken from the top view focuses on the user's shank and feet area within the rollator's parameter. Fig. 2. shows the anatomical representations of the linear and rotational measurement points measured with the user interface solution. The linear displacement of the swinging and stance foot is measured from the foot axis plane. The foot axis plane also provides measurement point for the feet external and internal rotations.

A. Rotaion and Linear Measurement

The approach used to determine the linear and rotational measurement of the user's feet is as follows:

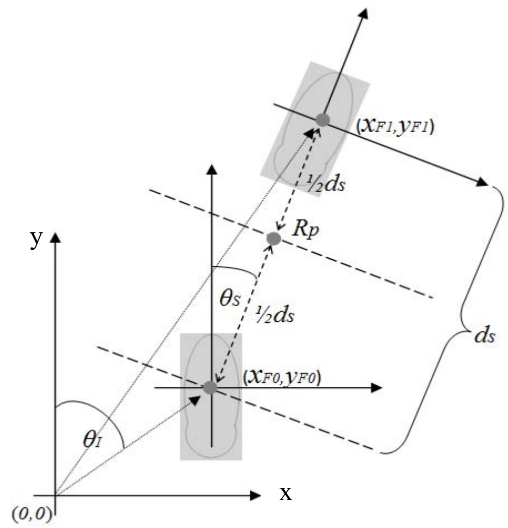

Fig.3. Human gait step tracking representation.

Tracking of the feet movement with respect to the moving camera is performed by using the previous frame's stance foot location as reference to the current frame feet location. The difference between the current and previous measured coordinates of the stance foot is used to translate the position of the feet in the current frame to previous frame. The angle from the vertical y coordinate (θ_I) with the distance from the origin to the location of the stance foot is used to rotate the translated coordinates of the feet.

In Fig. 3. the tracking of a person's gait step can be seen with a leg's stance foot at coordinate (x_{F0}, y_{F0}) and a leg's swinging foot at coordinate (x_{F1}, y_{F1}). The angle θ_I represents the image's reference frame in relation to the leg's stance foot coordinate (x_{F0}, y_{F0}). θ_S represents the angle of the leg's stance foot coordinate (x_{F0}, y_{F0}) to the leg's swinging foot at coordinate (x_{F1}, y_{F1}), measured by the heading of the leg's swinging foot at coordinate (x_{F1}, y_{F1}). The above frame system may be represented by a homogenous transformation as follow:

$$T_S = T_I \times T_{F_{ST}} \times T_{F_{SW}} \tag{2}$$

where T_S represent the translational and rotational components of the leg's stance and swinging feet tracked in an acquired image, with T_I the camera transformation, $T_{F_{ST}}$ the stance foot's transformation and $T_{F_{SW}}$ the swinging foot's transformation. The transformation matrix T_S then becomes:

$$T_S = \begin{bmatrix} a_{11} & \cdots & a_{13} \\ \vdots & \ddots & \vdots \\ a_{31} & \cdots & a_{33} \end{bmatrix} \tag{3}$$

$a_{11} = \cos(\theta_I + \theta_S)$

$a_{12} = -\sin(\theta_I + \theta_S)$

$a_{13} = x_{F1} * \cos(\theta_I + \theta_S) - y_{F1} * \sin(\theta_I + \theta_S),$

$+ x_{F0} * \cos(\theta_I) - y_{F0} * \sin(\theta_I)$

$a_{21} = \sin(\theta_I + \theta_S)$

$a_{22} = \cos(\theta_I + \theta_S)$

$a_{23} = y_{F1} * \cos(\theta_I + \theta_S) + x_{F1} * \sin(\theta_I + \theta_S),$

$+ y_{F0} * \cos(\theta_I) + x_{F0} * \sin(\theta_I)$

$a_{31} = 0$

$a_{32} = 0$

$a_{33} = 1$

The distance between the feet can be determined by:

$$d_s = \sqrt{(x_{F1} - x_{F0})^2 + (y_{F1} - y_{F0})^2} \tag{4}$$

The desired rollator position R_P is determined at the center of the two feet as the user's body is also assumed to be at the center of the two feet during a linear or rotated gait step. The desired rollator position R_P is then determined between the leg's stance foot coordinate (x_{F0},y_{F0}) to the leg's swinging foot coordinate (x_{F1},y_{F1}),

$$\overrightarrow{R_P} = \left(\frac{x_{F1}+x_{F0}}{2}; \frac{y_{F1}+y_{F0}}{2}\right) \quad (5)$$

The rollator's desired position and orientation R_P may then be used as the command to the motorised differential drive system of the Robotic Rollator.

IV. Results and Discussion

The results included in this section are for both the linear and rotational measurement of the feet. The measurements were performed on fixed paths with known distances and angled turns of 30˚ and 90˚ separately. The path results focus on testing the accuracy of the approach used in determining the orientation and position of the feet and that desired navigation of the robotic rollator.

Fig. 4. Image of the tracked feet.

Fig. 4. illustrates the tracking of the feet as two different objects during the user's walking movement. A bounding box is constructed around each foot of the user. Within this figure it is further noticed that both the user's feet and rollator's structure are clearly visible for analysis.

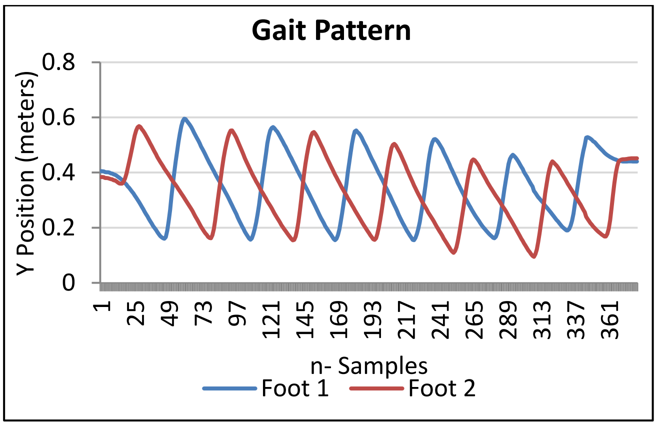

Fig. 5. Gait pattern analysis using a camera.

Fig. 5. illustrates the resulting linear gait pattern observed during the tracking of the user's feet. Foot 1 and foot 2 represent the user's right and left feet respectively during the stance and swing phases. A minimum linear distance is seen during the stance phase of the foot and the maximum distance results during the foot swing phase. The linear distances of the feet are equal when the right and left legs cross each other. The gait pattern results relate closely to the pattern observed from [9] using IMUs mounted on the upper thighs of the user, where the movement is related to that of a biped robot.

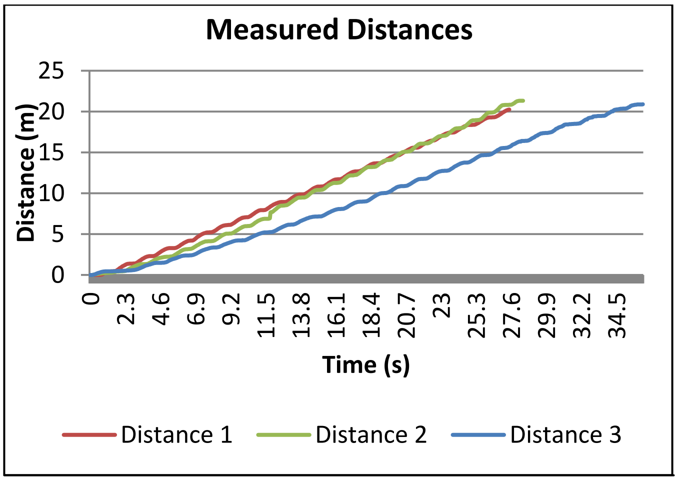

Fig. 6. 21m linear distance results.

Fig. 6. illustrates three linear distances measured over a path of 21m at different walking speeds. The path is divided into 0.5m sections and the user had to take a step distance of 0.5m on the markers. This is done to test the feet tracking accuracy. The zero distance change occurs due to the ground contact phase of the feet. Although the feet are in motion during this period the camera experiences a dead time in measurement. This may be noticed in Fig. 6.

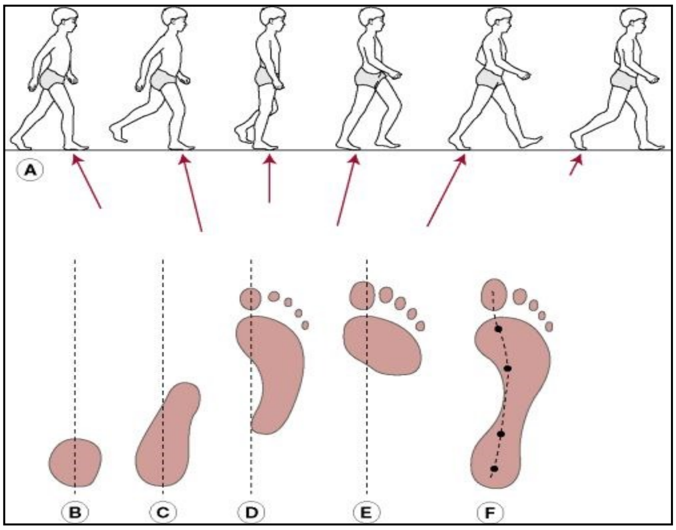

Fig.7. Gait cycle during the ground contact phases of the foot [14].

Fig. 7. shows the ground contact phases of the foot. The rotation movement of the foot during ground contact can only

be observed from the sagittal plane. The roll angle resulting during the contact, midstance and propulsive phases of foot ground contact cannot be easily sensed by the camera. The camera during this period sense the foot as being stationary although the user's body and feet are still in motion.

A State observer can be realised in order to compensate for the dead time resulting during the gait cycle and ground contact phases. This system is said to be observable with full reconstruction of the human gait states. The state observer is then the system that provides the estimation output of the observed system internal state related to its input and output measurements. The state observer will thus allow the reconstruction of the internal state of a system without having direct access, but simply starting from the knowledge of system inputs and outputs. A model of the human gait in terms of leg and feet phases with internal states will be necessary in this observer. Due to unavoidable inaccuracies in the human gait model and due to uncertainties, the states would be destined to diverge from the real state. On the contrary, this can be avoided by closing the loop, by feeding back the error between the measured and observed outputs. This error is multiplied by an observer gain K and reported as input to our human gait reproduction. This allows for a continuous adjustment of the rollator command, guaranteeing the coherency between the estimated and desired output. The implementation of an observer on the current system will only be considered for a later study.

In [9] the associated problem of dead time resulting during the gait cycle and ground contact phases is not experienced as a compass gait biped model is used resulting in continuous measurements, but with the disadvantage of a sensor connected directly to the user as mentioned in the introduction.

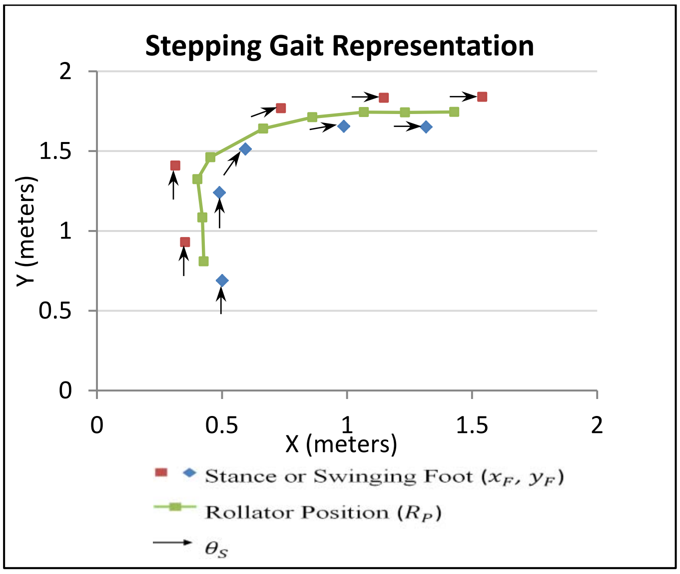

Fig. 8. Representation of the feet steps during gait.

Fig. 8. illustrates the step gait and rollator desired location. The position of each foot is shown by the blue and red points. Depending on whether the point is during the swing or stance phase of the foot it is represented by (x_F, y_F). The rollator position (R_P) indicates the desired position of the rollator during the stance phase of one foot and the swing phase of the other foot. θ_S shows the heading angle of the swinging foot which results from the direction of the swing foot respective to the stance foot.

The results for the position and orientation of the user's feet and rollator position (R_P) are graphically presented below.

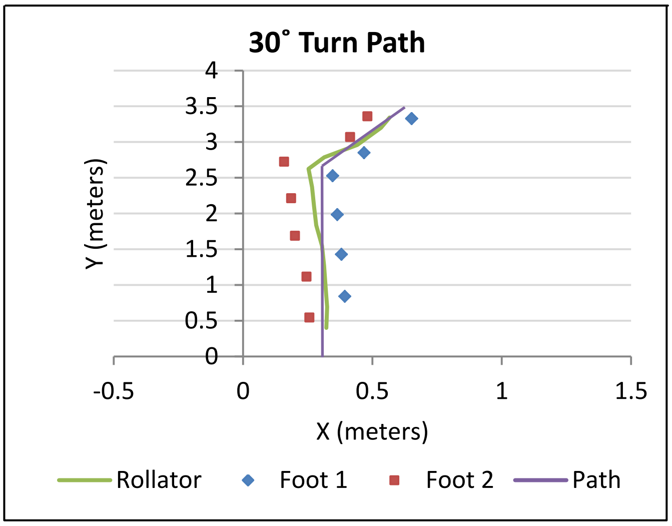

Fig. 9. Results for 30° turn path.

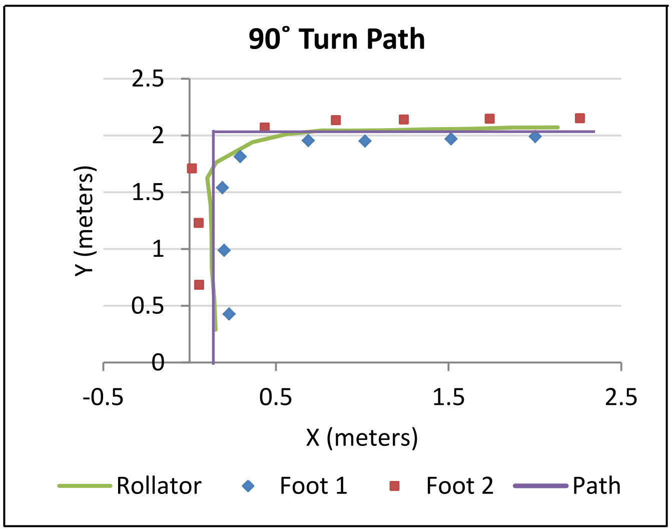

Fig. 10. Results for 90° turn path.

Fig. 9. and 10. illustrate the results for the 30° and 90° turn respectively. The blue and the red points represent the position and orientation of the each foot during the swinging and stance phases. The rollator path results from the desired rollator position and orientation (R_P). The rollator path is successfully mapped on the fixed paths with known distances and corresponding angles.

V. CONCLUSION

The paper presents a non-contact user interface solution for a robotic rollator. The tracking and analysis of the feet is performed using computer vision techniques with the help of a camera mounted on the rollator's frame to acquire video images of the feet motion. The feet were measured as end effectors to obtain linear and rotational parameters. The aim of the study is to obtain the desired rollator's position and orientation that are required to the command to the motorised differential drive system of the robotic rollator. The robotic rollator may be used as a mobility aid for navigating difficult terrains with ease. The robotic rollator may also be used as an effective rehabilitation tool by clinicians.

For further development additional cameras can be placed on the sides of the rollator to measure the motion of the feet from the sagittal plane, in order to compensate for possible dead time, due to stochastic human gait phases. With further developments on indirect user interface methods and impedance control algorithms a possible artificial control metaphor can be eliminated.

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