Can smart rollators be used for gait monitoring and fall prevention ?

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Can smart rollators be used for gait monitoring and fall prevention ?

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***Abstract*— Clinical evaluation of frailty in the elderly is the first step to decide the degree of assistance they require. This evaluation is usually performed once and for all by filling standard forms with macro-information about standing and walking abilities. Advances in robotics make it possible to turn a standard assistance device into an augmented device. The existing tests could then be enriched by a new set of daily measured criteria derived from the daily use of standard assistance devices. This paper surveys existing Smart Walker to figure out whether they can be used for gait monitoring and frailty evaluation, focusing on the user-system interaction. Biomechanical gait analysis methods are presented and compared to robotics system designs, to highlight their convergences and differences. On the one hand, monitoring devices try to estimate accurately biomechanical features, whereas, on the other hand, walking assistance and fall prevention do not systematically rely on an accurate human model and prefer heuristics on the user-robot state.**

I. INTRODUCTION

Ageing in society is a worldwide issue that especially impacts northern countries. In France, due to the high care cost and to the limited number of rooms in care institution, the solution that has been chosen by care-givers, frail people and their family is to maintain elderly at home the longest and in the best conditions by giving them an *adapted assistance*.

Clinical evaluation of frailty in the elderly is the first step to decide the degree of assistance they require. This evaluation is usually performed once and for all by filling standard forms with macro-information about standing and walking abilities, e.g. by measuring the time taken to walk $10m$. Advances in robotics make it possible to enhance a standard assistance device by adding sensors and actuators. The existing tests could then be enriched by adding a new set of daily measured criteria derived from the daily use of standard assistance devices. This monitoring will allow to evaluate gait in ambulatory conditions, to measure the evolution of some pathologies, to refine diagnostics and to distinguish autonomy levels. The assistance device is not meant to be an alternative for clinical frailty observation but rather as a complementary tool that gives field information. The data acquired on-line could also be used to control a robotics walker in order to prevent a fall. These new characteristics can extend the use of walkers to more diverse population.

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In this survey, we will focus on the use of a standard *rollator* equipped with sensors and actuators for monitoring. We will try to determine whether relevant information can be obtained from an equipped *rollator* without adding any sensor on the human body. This study then tries to answer the following questions :

1) What are the relevant features for walk analysis ?
2) How the use of a rollator distort the walking gait ?
3) Some smart walker already exists. What kind of data are they acquiring about human state and what kind of input are they using to maintain the system balance ?

In the first section, we will start with a biomechanical point of view by surveying studies led on elderly and rollator walking, and we will partially see to which extend studying the walk with a rollator may be relevant. In a second part, we will survey the existing robotics frame and their user interfaces. The first section is dedicated to walk *monitoring* with a smart rollator, the second one deals with walking *assistance* method and the last presents *fall detection* systems.

II. WALKING GAIT ANALYSIS WITH OUR WITHOUT ROLLATOR

Depending on the degree of assistance they need, people are prescribed canes, crutches or walkers [1]. Le latter can be legged walker or wheeled walkers (rollators). A rollator can be defined as a frame with three, or four wheels. It has handles with brakes, and in some case a seat, a basket and a tray (see fig. 1).

Fig. 1. 3 and 4 wheeled rollators

Static equilibrium is maintained when the body's center of pressure is positioned over the base of support. Loss of balance can result when the center of mass is displaced in relation to the base of support because of voluntary movements or external perturbations.The use of a walker increases the base of support, thereby allowing a greater tolerated range for center of mass positions. They can also prevent instability by allowing stabilizing reaction forces such as holding on or pushing against the ground.

Basically, standard four legs are dedicated to people that need assistance to maintain their balance or for those that require partial weight support [1]. Their use changes gait pattern and posture during a gait and requires good coordination for lifting up and placing forward the device during gait [2]. On the opposite rollators induce a more natural gait pattern but lack in stability. They are designed for people that need less weight bearing [2].

A. *Standard measurement of walking gait*

In order to design a useful system for clinicians we have first to understand what are the common features they use for walk gait analysis and what are the standard tools. The medical walk analysis can be divided in three steps : i) patient qualitative observation, ii) a description phase and iii) a biomechanical analysis. Description phase and biomechanical analysis depends on the equipment available in the medical center. The observed features range from spatio-temporal gait analysis to fine body motion analysis.

a) Elderly specific gait pattern: Ageing decreases the muscular force and changes the postural control and gait. It is not obvious to determine what is a ”normal walk” for elderly since each individual develops his own adaptation strategy to maintain balance. Some believe a slowed gait is a disordered gait, and others believe that any aesthetic abnormality, e.g., deviation in smoothness, symmetry, and synchrony of movement pattern, constitutes a gait disorder. However, a slowed or aesthetically abnormal gait may in fact provide the older adult with a safe gait pattern that helps maintain independence [3]. Patients are separated into three classes : *autonomous*, if they can walk freely without assistance, *frail* and *dependant* if they can not walk without assistance device.

To assess the frailty degree, standard tests are performed : *10 meters walk test*, *Tinetti balance test* and *Timed Up and Go* test [4]. In the latter, the patient sits on a chair with his back against the chair back. On the command ”go”, the patient rises from the chair, walks 3 meters at a comfortable pace, turns, walks back to the chair and sits down [4]. Tinetti test studies user postural abilities. Other tests can be added to evaluate transfer abilities and muscular force are also evaluated. Balance is tested by evaluating intrinsic balance by changing arm height, extrinsic balance by pushing the patient and simple support capabilities opened eyes or blind.

Physicians observe patient overall posture and arm swing during the walk. They also examines gait parameter such as gait width, step length, cadence and high of heels during a walking cycle, metatarsus-tibia angle, position of the foot when walking.

Indeed, some specific patterns can be detected by studying walking gait :

- After a fall or a stroke, people are subject to retropulsion syndrome which make them walk on the heels, enlarge their support base, and increase the knee flex.
- A stepping may be related to antero lateral leg muscles paralysis along with a loss in foot’s dorsi-flexion, making the patient lift his feet higher that necessary.
- Parkinsonian festination corresponds to a speed up of the pace. The patient bends with an increase flexion of the knees.
- Hemiplegic pyramidal spastic gait induces a rigid leg and foot sliding on the ground
- Multiple infarcts syndromes are related to small steps where the heel of one foot does not reach the toes of the other foot
- Heeled walking can be related to sensory diseases
- Charcot’s gait increase the support base, i.e. the gait width
- Waddling gait can be related to muscular force loss or D vitamin deficiency for elderly
- Zigzag gait is linked with vestibular syndrome

Notice that these pattern rely on standard spatio-temporal analysis of gait. 3D feet positions during the walk seem to be the key component in gait analysis. But it is may be due to the fact that the current gait analysis tools can accurately measures this feature. If other characteristics could be as easily extracted, the pattern might be enriched with other dimensions.

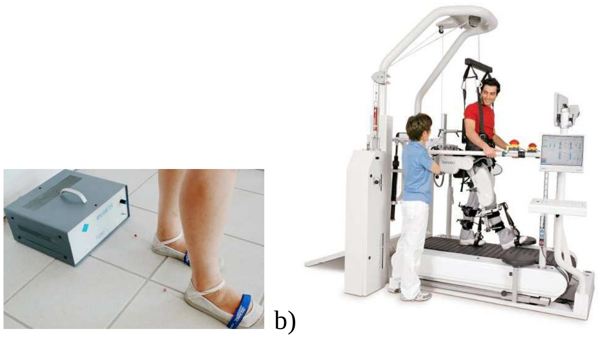
a)  b)

Fig. 2. From locometer to lokomat a) Bessou’s locometer (Walkmeter ©), consists of two wired that are tied to the feet. Wired expansion is measured in time, witch allow to compute spatio-temporal analysis.b) Lokomat ©is a complex treadmill for walk analysis and rehabilitation

b) Standard gait analysis tools: A standard inexpensive gait analysis device is the Bessou’s Locometer. It consists in measuring the length of two cables tied to the feet (see fig. (2)). It allows to accurately measure simple/double support phases, step length, cadence and velocity. Walkway or treadmills equipped with force sensors may give additional information about foot pressure distribution, centre of pressure trajectory and center of gravity trajectory. Further biomechanical investigation can be obtained using body segment tracking thanks to motion capture equipment (eg. Vicon or Qualisys motion capture system).

The human model kinematics can be represented as a system made of articulated rigid bodies. The number of links depend on the analysis to perform. For walking analysis, the model is sometimes simplified, assuming the walk to be symmetrical. It is then limited to the study of one lower limb in the sagital plane. Head and trunk are then fused in one only body and the arms motions are neglected [5]. Joints are marked with reflecting spheres and their trajectories is tracked thanks to a motion capture system [6].

In addition to the kinematics analysis, extrinsic forces can be analysis thanks to force-plates or walkways, giving information about system mass dynamics, which could give useful information to infer balance capabilities. And finally, if pressure sole are available, the foot pressure distribution can be studied, e.g. to check if the elderly is walking on the heel or have a proper use of the toes for propulsion.

A grasping force test is sometimes added to estimate the muscular force, assuming that the loss is uniform on the whole body.

The first objective is to provide physicians with the features they are used to process to evaluate elderly frailty, while maintaining a low cost and ensuring a good ease of use and by embedding all the sensors on the walker without equipping the patient. And at best, the intelligent walker could deliver others relevant features that will enriched the existing feature set. But, can we measure relevant features with a rollator for patients that need it as well as patients that are still autonomous ? Does the gait pattern change significantly using a rollator ?

B. Standard biomechanical analysis of rollator Walking

Very few work have studied rollator walking specificities, although such information are relevant to make a decision on its use or whether the user needs some additional muscular or balance training. This information is also mandatory for a smart walker to assist the walk or compensate for loss of balance.

In a early study, it has been shown that the walking performance in elderly subjects measured in terms of distance, cadence and velocity is improved when they walk with a rollator [7]. And the rollator users are generally satisfied with their rollator and consider it a prerequisite for living a socially active and independent life [8].

Studies on walking with canes or poles have shown that these walking aids reduce the load on the lower extremities [9], [10]. The rollator might also reduce the load on the leg muscles and the joint to some extend as well however, the walking change in gait parameters when walking with a rollator been quantified in very few studies.[11] observes a reduction in the vertical ground reaction force during rollator walking. This study has been refined in [12] that studied the biomedical effects of walking with a rollator on the walking pattern of healthy subjects.

The set up consists in two force platforms and a marker based video tracking system. Methodology follows [13] for the setting up of 15 spherical markers and the use of a three-dimensional inverse dynamics method. Results, for tested healthy people, show that rollator walking did not result in an overall unloading of the muscles and joints of the lower extremities but on a selective one. The unloading of the ankle and knee seemed to be partly compensated by an increase in the hip extensor moment, which probably was needed to push the rollator in a forward direction and keep its horizontal velocity. It is due to the increased forward flexion of the trunk during rollator walking. It concurs with other studies that have observed increased hip flexion along with an increase in the hip extensor moment [14]

Dealing with the pattern gait characteristics, they prove the following specificities :

- increased hip flexion;
- decreased ankle dorsi-flexion and knee flexion;
- significant decreased ankle and especially knee joint moments;
- increased hip extensor.

Theses characteristics have to be taken into account when examining rollator walking.

C. Partial conclusion

Physician usually study spatio-temporal gait parameters. Standard biomechanical tools provide either some of these features or all of them. It can be shown that some walking patterns give relevant indications on specific diseases. Yet, using a rollator may alter the walking gait, changing at the same time the measure pattern. For example, decrease ankle dorsi-flexion is induced by rollator walking and could be interpreted as antero lateral leg muscles paralysis in a free walk. Before drawing diagnosis on patient by using a rollator, we have to make sure that the criterion are valid for a rollator walking. Yet, some features, such as pace and asymmetrical walk can still be observed directly during rollator walking.

III. Intelligent walkers

In this section, we will survey the existing smart walkers, and we will limit our scope to standard medical frame equipped with sensors. Recently, *hand-free* walkers have been introduced, e.g. the KineAssist [15] or the Walkaround [16]. These systems are promising in terms of balance recovering and they have the advantage of leaving the hands free for daily tasks. Yet, in this paper we will focus on common wheeled walker that connects to a person at the hands.

We will investigate the type of data acquired about user's state for three applications : i) gait monitoring, ii) user intent estimation for navigation and iii) fall prevention. Smart walkers may be used to analyse either the environment or the user's behaviour. Environmental data is dedicated to navigation purpose, such as obstacle avoidance [17], wall following [18], slope compensation [19] or localisation [20] [21]. Even though these functionalities are relevant for people autonomy, especially for the visually impaired, these functionalities are out of the scope of this survey. A thorough survey on assistance mobility device, focusing on smart walkers can be found in [22], [23].

A. Monitoring the user state

Some of the existing Smarts walkers aim at tracking the trajectories of gait features in order to monitor health. The great advantage of such systems is that the user stands at a roughly known position with regards to the walker. Body segment localisation is then made easier.

c) Using force sensor to evaluate the walk gait parameters: Walker can be equipped with force-moment sensors mounted on the walker handles [24], [25], or under the forearm [22], [26] to passively derive some gait characteristics. In both cases it is assumed that the force and moment recorded have cyclic changes reflecting the gait cycle and that these changes depend on basic gait features (cadence, stride time, gait phases).

The iWalker [25] quantifies loads exerted through the handles an frame and standards spatio-temporal parameters (such as speed and distance). In [24], a direct comparison between motion capture and force-moment data was studied to detect significant pattern in the force signal (cf. fig. 3). The lateral sway motion of the upper body reflects in peaks in vertical direction and in the corresponding forward moment signal. These peaks coincided with the heel initial contacts and. The forward propulsion force applied by the user is related to the toe-off event from the right and left toe. Finally, the stride (ie. duration of a gait cycle) can be computed from two heel contacts.

In [26], a method based on Weighted Frequency Fourier Linear Combiner, is introduced for the same standards gait parameters extraction from force data.

d) From odometers and accelerometers: Walker wheel motion measurement can also be used to estimated the user state [17], [27]. The Personal aid for mobility and monitoring project (PAMM) [17] developed health monitoring tools. The PAMM smart walker is an omnidirectional walker design for walking assistance with navigation and monitoring functionalities (cf fig. 3). Its sensors record user speed and compute the stride-to-stride variability, which have been shown to be an effective predictor of falls. A power spectrum analysis on PAMM's velocity allows to estimate user's stride length and frequency. Besides, the shape of the power spectrum is related to the gait symmetry. Indeed, for a symmetric gait, the energy is located at twice the stride frequency. However, the system can detect asymmetric gait as spectrum with energy located at the stride frequency and at higher frequency. An asymmetrical gait could be an indicator of a physical injury or a minor stroke.

a) 

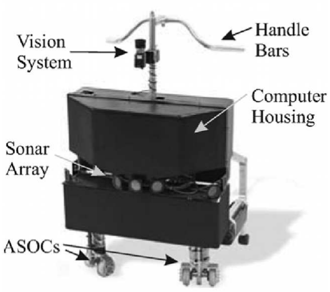
b) 

Fig. 3. a) Medical Automation Reasearch Centrer (MARC) Smart walker [24] b) The PAMM Smart Walker for walk assistance and health monitoring [17]

e) Feet/User position using ultrasonic sensors or cameras: Direct measurement of body segments may be obtained by using ultrasonics sensors or cameras [22], [28]. A vector of ultrasonic sensors can be mounted on the walker to scan the space between the user and the walker and determine coordinate of each leg without adding any marker on the patient [22]. In [28], a camera is mounted on the frame and observes markers on the toes. This marker based toe tracking algorithm allows to calculate step width and provide an accurate assessment of foot placement during rollator use.

The main issue when using that kind of device is that the accuracy of the leg localisation depends strongly on the clothes that the user wears. It is a drawback with regards to method based on odometers or force sensors. The method proposes in [28] by-passes this point by adding markers on the toes. Yet it also by-passes our constraint not to equip the user in order to ensure acceptance and ease of use.

B. Assisting the walk by estimating user intent

Some intuitive command schemes based in user intent analysis have been proposed. The point is to determine how to give the control to a user with taking into account his possible cognitive degeneration. Furthermore, data could be distorted by a pathological gait.

f) From user force interaction: User intent can be inferred from upper-body force interaction in rolator assisted gait [29], [17], [30]. In [30], two 3D force sensors are installed under the forearm supporting platforms (see). The elbow lateral motion is then restricted and the weight of the user on the sensor is increased, leading to a more stable configuration. The force data are processed to isolate three components : high frequencies that are due to the vibration induced by the wheeled friction on a non smooth floor, users's trunk oscillations that are directly related to user gait and user navigation command. The two first components can be monitored and analysed for gait analysis [26], whereas the third component can be used to estimate user intention [30].

PAMM systems [17] use a six axis force/torque sensor attached to the handle as the main user control interface. The force/moment signals are interpreted for motion control by using an admittance controller. They contain the user's intention as well as support and stability information about the user. The admittance model can be tuned for each individual user. It can be made manoeuvrable and light for agile users and slow and stable for someone who needs more support. The admittance is the transfer function from the user's force and torques to the PAMM's velocities. The response of the PAMM is obtained by solving the dynamics equations and then solving the inverse kinematics of the physical system to get the actual actuator velocity. The challenge is then to design the appropriate dynamic model to give the user a comfortable feeling. This is done by choosing a metric to evaluate the performance of the model so that the operator effort is minimized.

The MARC Smart Walker [24] is a three wheeled walker also equipped with force/torque sensors on handles (in addition with sonar and infra-red sensors). The control of the

MARC Smart Walker is performed by fusing user intent and walker intent to control the orientation of the front wheel. Walker intent is computed from the information on the surroundings that is acquired by the sonar and infra-red sensors.

Fig. 4. Murata walker has been unveiled at CEATEC Japan exhibition during fall, 2011

g) Using inertial data and inverse pendulum model: The Murata walker has been unveiled during fall, 2011 (see fig.4). It is a two wheeled walker that uses inertial information to maintain human-walker balance, considering human body as an inverse pendulum. If a fall is detected, the system brakes to help the user recovering his balance.

C. Preventing the fall

h) User/Walker distance: The walker-uses relative distance can be used to classify the states between a *walking state*, a *stopped state* and an *emergency state* [31]. A laser range finder mounted on the walker acquired the position of the knee with regards to the walker frame. It is assumed that the position of the feet is at the vertical of the knee position, and fixing the human frame in the middle of the feet. User velocity is estimated from the walker velocity obtained by odometers. The *stopped state* occurs when both the walker and the human velocities are null. To distinguish the *walking state* from the *emergency state*, user-walker distance is used. A normal distance distribution is computed to determine the *walking state* based on user data. The robot control tries to bring the user distance right to the mean of the walking state distance distribution.

i) Observing human posture: In [32] the RT-Walker (cf fig 5) is equipped with laser range finder and perform an estimation of the kinematics of a 7-link human model. The model is used to estimate the position of the user center of gravity (CoG) in 3D. A stable region is determined by analysing the distribution of the C.o.G. position for three subjects with different physiques who walked for 100 seconds with a walker. If the C.o.G is out of the region, the user may fall. The system then brakes enough to compensates for its lightweight and prevent the fall. Notice that the fall detection is restricted to the sagital plane.

In [33], The RT Walker is equipped with vision sensor to classify the user state among four classes : sitting, standing, falling, and walking. The classifier is based on heuristic on the distance between user head, hands and shoulder. Basically, the vision algorithms are based on head tracking, and skin detection. Shoulder detection is performed by finding the higher points of a uniform color region under the head, which seems to lack robustness with regards to environment properties and user clothes.

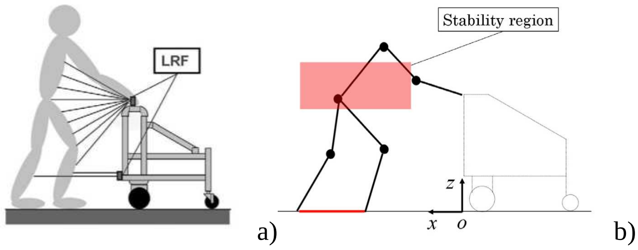


Fig. 5. RT Walker prototype [31] is a passive device using servo brakes rather than actuators for obstacle avoidance and fall prevention. a) is the Laser range finder set up that is used to estimate a 7-link sagital human body model [32]. b) depicts the C.o.G. stability area.

Fig. 6. The Assisted Navigation Guide (ANG walker) [34] is equipped with various sensors and a bistable clutching mechanism

j) Observing walker odometers: The Assisted Navigation Guide (ANG walker) is based on a 4 wheeled Rollator [27] equipped with accelerometers and wheel encoders (cf. 6). The rear wheels are motorized, a bistable clutching mechanism allowing to clutch and unclutch the actuators at will. Two modes are then available : *free mode* were the motors are unlashed but the wheel rotation are measured and the *motor mode* where the motor are clutched and produce motion help or servo brakes. The acceleration of the walker and the velocity of the wheels are directly linked to the user state. The fall detection system is based on a processing of these values.

D. Partial conclusion

Monitoring systems allow to estimate biomechanical features in ambulatory conditions, i.e. in uncontrolled conditions. Information about the walker itself (odometry, inertial parameters) or user-walker interaction seems more robust in these condition than laser data, video or distance sensors because they do not rely on environmental parameters such as user clothes and lightning condition. Yet, these sensors can provide useful and complementary information about user posture.

Walking assistance based on user intend allows to control the direction of the walker. Fall prevention algorithm tend to draw the boundaries between "normal situations" and "risk of fall". Most of the time, the control strategy consists in braking to stop the system.

IV. Conclusion and future works

Standard biomechanical features such as walking speed, cadence, step length can be estimated from observing rollator walking. Yet, rollator walking constraints the walk and modify posture and gait. For example, arm swing is a relevant parameter for balance estimation that can not be observed. Some other information seems hard to obtained without equipping the user (3D feet positions, force pressure distribution on the ground). On the opposite, it provides additional information with regards to a standard locometer, such as gait width.

This survey on existing smart walker raises several questions. In previous works, the equilibrium model is restrained to sagital plane and most of the works assume the walk to be symmetrical. Would it be possible to use a rollator to evaluate out of the plane motions and falls ? Regarding modification of the posture and gait, further study should focus on human-walker model to asses if we can evaluate autonomous walker with an assistance device they do not need. If the user does not use the device properly, could we still measure some relevant gait parameters ? And finally could we obtain an estimation of a free gait with studying rollator walking ?

Use of 6 D.o.F. sensor allow to have an idea of the force someone put on a handle. It might be linked with its global muscular force.

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