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Smart walkers: an application-oriented review

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SUMMARY

In this paper, a development method for smart walker prototypes is proposed. Development of such prototypes is based on technological choices and device evaluations. The method is aimed at guiding technological choices in a modular fashion. First, the method for choosing modules to be integrated in a smart walker is presented. Application-specific modules are then studied. Finally, the issues of evaluation are investigated. In order to work out this method, more than 50 smart walkers and their pros and cons with respect to the different studied applications are reviewed.

KEYWORDS: Smart walkers; Mechanical design; Strolling control; Gait support; Unbalance management; Navigation help; Sit-to-stand assistance; Evaluation methods.

1. Introduction

Due to a global increase in life expectancy, the world population is ageing.[1] Physiological ageing entails deficiencies in walking capabilities. These deficiencies encompass a slower pace ("speed of walking remains stable until about age 70; it then declines by about 15%/decade for usual gait and 20%/decade for fast walking"),[2] a modification of proprioception (sense of the position of joints and state of muscles),[3] a reduction of inner ear efficiency.[4] In addition, these "normal" deficiencies stack on the repercussions of injuries and diseases sustained during a long life span. Due to ageing, "approximately 28–35% of people aged of 65 and over fall each year increasing to 32–42% for those over 70 years of age".[5] In turn, falling and fear of falling greatly restrict autonomy of elderly people.[6]

Clinicians prescribe conventional walking aids (canes, crutches, walking frames and wheeled walkers) in order to assist walking. These devices relieve lower limbs from some weight bearing by transferring it to the upper limbs.[7] In addition, they increase the support polygon, allowing a wider stable range of motion of the body's centre of mass (COM).[8] However, these devices present limitations. For example, during sit-to-stand (STS) motion, users have to change their support surface during the transition (support on the chair for STS and then on the walker in order to begin walking).[9]

Smart Walkers (SWs) aim at partly fulfilling the different needs and constraints by expanding functionalities of conventional walkers in order to further improve mobility. However, as loss of mobility in elderly people is multifactorial, researchers are restricted to a single application (one kind of pathology and one type of use). For example, Lacey *et al.*[10] focus on people with both impaired sight and severe arthritis whose assistance requires combining a white cane and a walker.

A SW that fits all applications is an unrealistic target because goals for different applications are often contradictory (e.g. cost versus complexity versus robustness). This observation leads us to ask: how to propose a method to develop SW for a given application?

Martins *et al.* proposed a first review[11] on walking aids including SWs classified according to the different functions and focusing on the human machine interaction aspect of robotic walking aids.

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They proposed a second one[12] on SWs classified according to functionalities and focusing on control and monitoring. Instead of this functional approach, we take the application point of view. Starting from an application, our method aims at helping designers to choose the modules most adapted to their future SW.

Even if applications are all different, some modules are always required for a SW: all SWs, as the conventional ones, have a mobile base and are supposed to support and stabilise the user.[13] The optimal mobile base differs depending on the application, a point we discuss in part 2. The way to choose modules that help in stabilising users is presented in part 3. Specific applications, such as guiding a blind person to access different facilities of a retirement home, requires specific modules that are investigated in part 4 to overcome cognitive and/or sensory deficits. Some special modules designed to adapt to daily life transition phases are evaluated in part 5. The method of development encompasses the testing part. As SW are clinical devices, a clinical evaluation is mandatory, leading to issues discussed in part 6.

2. Accompanying Locomotion of Users

Walkers are mainly prescribed for improving the autonomy of users by facilitating their locomotion. Thus, in order to help users, the mobile base of walkers should remain simple while not limit their displacement possibilities. As highlighted later in Section 2.4, these goals tend to oppose each other. This part proposes a method for comparing and choosing an adequate structure for the mobile base of the SWs according to environmental requirements.

2.1. Locomotion evaluation criteria

Similarly to classical mobile robotics, we use three criteria inspired by Böttcher[14]: stability, maneuverability and operability to compare the different structures of mobile base for SWs.[†]

2.1.1. Stability criterion. This criterion is the most important as it is a security criterion. It quantifies the ability to avoid overturning in any use case. It encompasses both straight line and turning use cases. Because of its sensitivity to vertical weight distribution and external loads, we choose the force-angle stability criterion used by Alwan *et al.*[15] to evaluate stability. It is obtained by estimating the COM resultant force of the "user-SW" partnership and by evaluating the angles between each tip-over normal axis and the resultant force direction. The criterion is the stability margin computed by the product between the minimum of these angles and the resultant force value.

2.1.2. Maneuverability criterion. The maneuverability criterion quantifies the ability of SWs to move in all directions. Campion *et al.*[16] propose the degree of maneuverability δ_M. This degree classifies SWs in only two categories: the omnidirectional SWs ($\delta_M = 3$) and the NOSWs ($\delta_M = 2$). With a NOSW, users have to maneuver to access some places. However, the difficulty to maneuver in this case really differs depending on the SW. The difficulty to maneuver is directly correlated to the distance between the centre of rotation of the SW and the user. This difference is not observable in Campion's scale.

In order to overcome this deficit, we propose a maneuverability criterion with three levels: $M1$, $M2$ and $M3$. The level $M1$ represents non-omnidirectional structures that are hard to maneuver ($\delta_M = 2$ and the centre of rotation is far away[17]). The level $M2$ is also for $\delta_M = 2$ but with a small distance of the centre of rotation[18] (around 20 cm). The level $M3$ corresponds to omnidirectional structures ($\delta_M = 3$).

2.1.3. Operability criterion. The control criterion evaluates the number of motors required for operating the motion of the SW. The highest levels of this criterion are achieved when SWs use only motors to move wheels in their forward direction. We define two levels for evaluating the SWs that require steering: level O1 (two motors in the forward direction and four to steer[19]), and level O2 (two motors in the forward direction and two for steering[20]). Furthermore, we propose three additional levels for distinguishing groups in which motors are only needed for forward motion: level O3 (four motors[21]), level O4 (three motors[22]) and level O5 (only two motors[23]).

† The concept of controllability described by Böttcher[14] is used with the name of operability to avoid confusion with other definitions of controllability.

2.1.4. Conclusion. The operability criterion is in general negatively correlated to maneuverability. For example, on the one hand, non-omnidirectional robots with an Ackerman structure are easy to operate but hard to maneuver, on the other hand, omnidirectional structures require more complex control strategies to be operated but are easier to maneuver. Mobile robots cannot maximise operability, maneuverability and stability for every environment. When designing SWs, developers can use different wheel types and arrangements. We will first consider specifications and needs according to the context of use. Then, the different choices of wheels and their consequences on the three "mobile robotic" criteria will be studied.

2.2. Environmental requirements

Designing mobile robots requires environmental parameters issued from the use cases. These parameters can be static such as the type of ground, type and size of obstacles, angles of slopes and the emptiness of the space. But dynamic parameters are also essential: Will the robot move with other robots? Will it be in contact with humans? What can jeopardize its integrity? How could it be dangerous?

These parameters can be translated into needs for stability, operability and maneuverability. Some parameters will induce choices relating to reliability, price, safety, . . .

In order to qualify the relevant environmental parameters, the three main area in which SWs are used are investigated.

2.2.1. Hospital or nursing home facilities. These institutions are the most adapted environments for using SWs. They alter the environment for facilitating users' mobility (e.g. no carpet, large doors, lifts). Their space is not crowded, obstacles to pass are scarce and small, slopes are gentle.

2.2.2. Home. This environment presents more difficulties. Its spaces are often narrow, small obstacles such as carpets are common, beds or chairs can be too low but slopes are usually gentle. If the hospital environment is taken as a reference, the size of wheels has to be higher in the house (to pass obstacles), safety has to be improved because more elements can jeopardize the stability of a walker in a house.

2.2.3. Outdoor (Country or City). This environment is the most challenging. It can be wet, requiring the SW to be waterproof. Its ground can be much more bumpy and much less predictable. Outdoor environments are generally less crowded than indoor environments but ground irregularities are very challenging. Its slopes are also challenging issues.

2.2.4. Influence on the mobile robotic criteria. The criteria to focus on when designing SWs should match the SW environment. For instance, operability can be more important than maneuverability in outdoor environments. Conversely, SWs designed for outdoors environments should put more emphasis on operability as later shown in Section 2.3.

Beyond the environment, the purpose of the SW influences the preference towards operability, maneuverability or stability. For instance, if the expected purpose is assistance, higher maneuverability is required. When the purpose is to motivate for rehabilitation, the exercise can be performed in an open space with a lot of straight lines and maneuverability is no longer the highest priority criterion.

2.3. Choice of wheels and consequences for smart walkers

Currently, six types of wheels are used in SWs (Fig. 1): fixed wheels, centred orientable wheels, off-centred wheels, Swedish wheels, spherical wheels[24] and Active Split Offset Casters (ASOC). Most of the available SWs use fixed wheels and off-centred wheels (also called caster wheels). Only a few SWs integrate ASOC or similar wheels.[25–28] In order to classify the different wheels, we assumed that the environment is a personal or nursing home, because such an environment is the most common for using SWs.

2.3.1. Enabling omnidirectionality. The first chosen criterion is the ability to build an omnidirectional SW because from our understanding, non-omnidirectionality increases the risk of falling. Indeed, to move in a house, the user has to maneuver a lot to reach his/her target when using a non-omnidirectional SW (NOSW). Consequently, the user will have a tendency to stop near the goal and, to use furniture support around him/her to avoid another maneuver, increasing the risk of falling.[29] In addition, with a NOSW, users could feel slowed down and suffer the effects of fatigue. These feelings could lead to

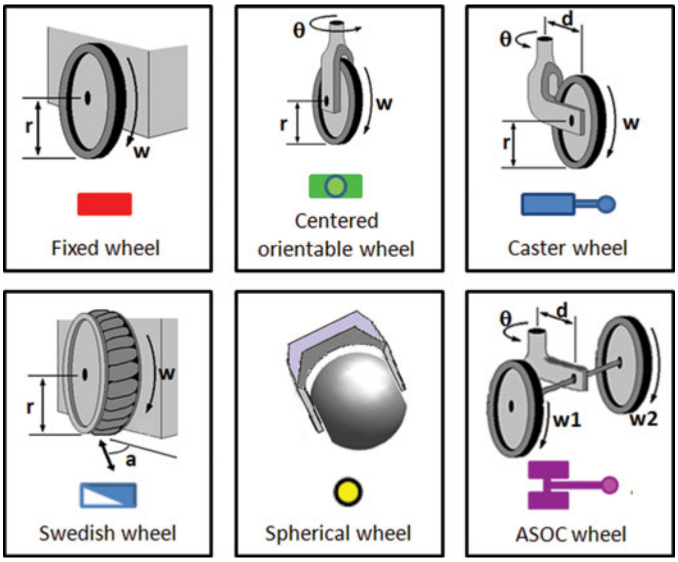

Fig. 1. Description of the wheels used to design Smart Walkers.

rejection of the device. It is not possible to push a NOSW sideways, yet user appreciate being able to do this at the end of use.

2.3.2. Tolerance to ground irregularities. The second criterion is the tolerance to ground irregularities. Some wheels can generate vibrations that are unpleasant for SW users. These vibration cause the user to stiffen his/her arms, leading to discomfort and fatigue. The ground criterion also includes a quantification of the ability to pass over small steps because the user might reject the device.

Swedish wheels are less tolerant to ground irregularities than conventional wheels.[25] This low tolerance to ground irregularities involves a low ability to pass over small steps, making Swedish wheels less tolerent than the others.

2.3.3. Ease of movement. Finally, the last criterion used for this selection is the ease of movement. It is assumed that the user will use the SW in a straight line more often than he will turn.

According to the different mechanical power transmissions, some wheels are easier to move in the forward direction and others in the steering direction. The choice of wheels directly impacts the operability of the devices that will be designed. Wheels that are more difficult to move in the forward direction are more likely to slip and those that are difficult to steer imply a higher coordination of the whole device to avoid internal constraints.

Spherical wheels[24] can be considered an exception because the inverse correlation between the forward and steering direction is not verified but they have a friction transmission that is less efficient than those used for conventional wheels. Consequently, it is harder to apply forward motorisation through them. Additionally, the use of wheels that are more difficult to move involves more powerful actuators and therefore greater weight. If the user has to move the SW without actuation because of power issues, light weight is preferable.

SWs must not be restricted to the forward/backward direction. When considering the ease with which wheels are turned (for all wheels except the fixed wheel), spherical wheels are easier to turn than caster wheels because no steering movement is needed. ASOC seems to be a compromise between these two kinds of wheels regarding this criterion. Indeed, turning this wheel requires a change of mechanical configuration but does not require turning the wheel directly around its axis. This low-friction change of configuration allows the use of smaller actuators.

The “ease of movement” criterion therefore first rejects spherical wheels and then caster wheels. The whole process of selection is summed up in the Fig. 2. In conclusion, ASOC is the kind of wheel that most fits the application aimed by SWs. During this analysis other criteria have been identified: high load capacity, simplicity and precision. They have been dismissed because they were not relevant to the application. The rationale of this rejection is presented in the following.

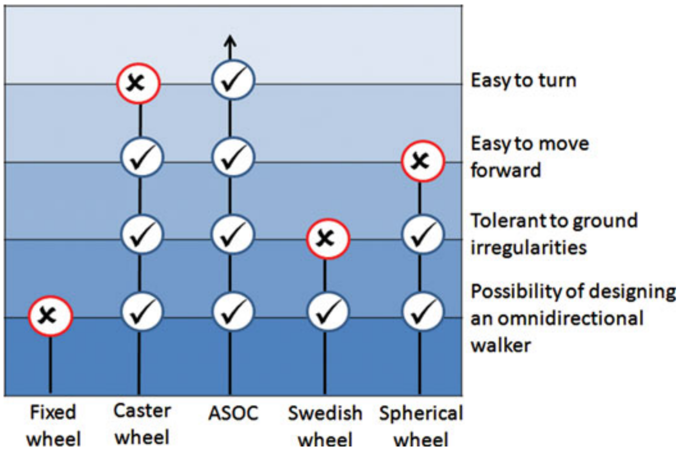

Fig. 2. Comparison of the different kinds of wheels.

2.3.4. Load capacity. Wheels for a SW must be able to support the weight of the device but also the total (user, SW) weight in case of incidents. However, all the considered wheels, even the spherical ones[24], can be sized to support the required weight. Consequently, the wheels will not be compared using the load capacity criterion.

2.3.5. Mechanical simplicity. It can be translated into price or reliability criteria. As some of the wheels are still at the research stage it is difficult to compare the different wheels according to their price. Reliability is obviously highly influential when designing a SW: the user should not be put at risk by the failure of the device. However, wheels that could be rejected under this condition are the newest ones for which robustness test are not yet available. For this reason, this criterion will not be considered.

2.3.6. Positioning precision. Precision in the control of a device can be representative of the operability of the system. If the position is not well known, it is hard to define where the system must be in the following instant. Some precision issues have been reported for different wheels (Swedish wheels for example), but the worst case of imprecision is lower than 1 cm. For this application, the expected range of precision is around a few centimetres because even with walking troubles, the user can adapt to variations of this magnitude with movements of the trunk and arms without feeling instability or discomfort. This criterion is therefore dismissed in the comparison of the wheels.

2.4. Analysis of the different proposed structures

Given the evaluation of available wheels, we can estimate the maneuverability, stability and operability of each available SW as a whole. We can classify the existing SWs found in the literature according to these criteria.

First, in order to evaluate the stability of the devices according to the force-angle criterion, the mass distribution and distances of the device are required. Since these data are not available, only the main differences according to stability will be discussed here.

SWs with less than four wheels are rare. Indeed, the stability of a two wheeled device[30] has to be continuously maintained with actuators. In addition, the user can only act on the device close to the line of the two wheels to limit the efforts needed to maintain the inverted pendulum. Here, the user has to adapt to the SW; it can lead to a risk of falling.

The three wheeled SWs[15,27] also present a risk of falling due to stability of the device. The support polygon of such a device becomes a triangle and the walker can quite easily fall over around one of the support triangle edges.

Stability issues still exist for the SWs with more than three wheels and some teams had to add wheels to ensure the stability of their devices (five wheels[31], six wheels[32,33] and even seven wheels[34,35]). But generally, these problems seem to be solved and designers take care of distributing the mass and placing the centre of gravity as low as possible.[36] An original solution of variable footprint (in width) to improve stability was proposed by two teams. Bülher *et al.*[37] propose to extend the support

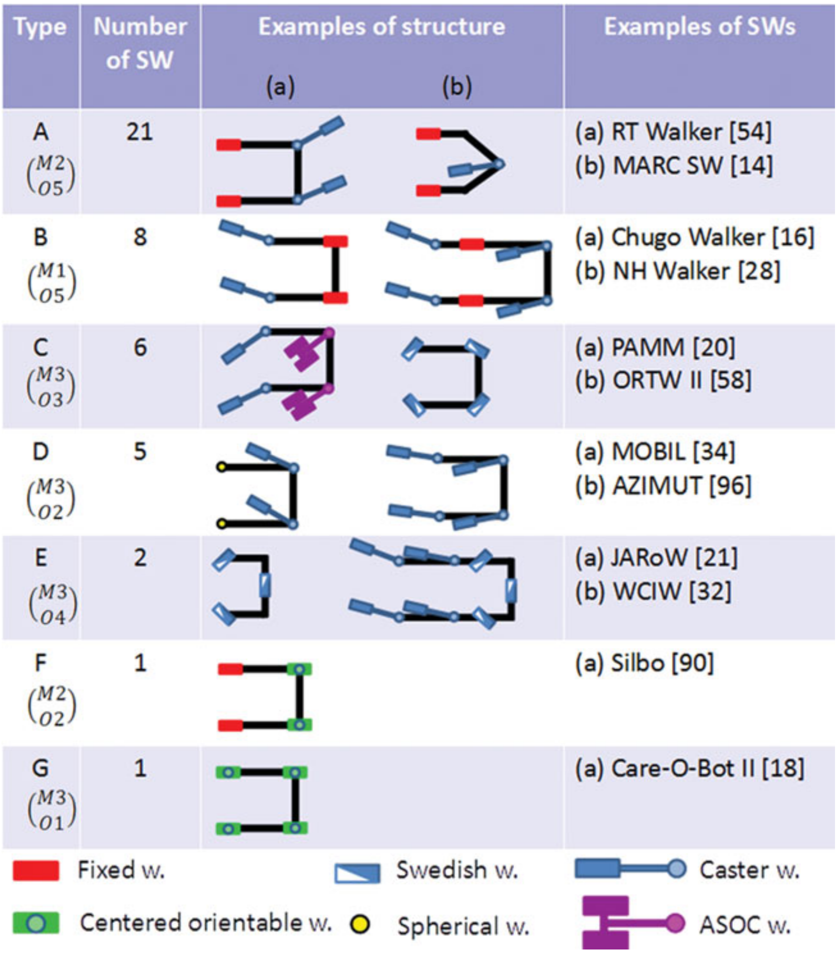

Fig. 3. Table of the different types of SW according to maneuverability level (M) and operability level (O).

polygon when the user wants to stand up. Ye *et al.*[35] maximise the SW footprint during strolling and minimise it only to go through doors. The footprint can also be changed in length in order to improve stability for stand-up motions.[34]

To compare SW using the two remaining criteria (maneuverability and operability), seven categories are distinguished and presented in the table in Fig. 3. These categories are organised according to the number of SW they contain. The A category encompasses the most common configuration in research SWs: two caster wheels in front and two fixed wheels at the rear. Most of the rollators available on the market also have this configuration. It allows a simple structure. Only two motors are required to control this device, giving it the best level of operability. The centre of rotation is between the two rear wheels and thus not too far from the user, giving it a middle level for maneuverability. This analysis is conducted for all the different SWs structures.

To better compare the different categories of SW according to operability and maneuverability, each category is shown at the coordinates (level of maneuverability, level of operability) in Fig. 4. The perfect category would be placed in (M3, O5) with the best level on the two criteria. In reality, it can be seen that three types seem easily operable while keeping good maneuverability : types E, A and C. Type E seems the best but all devices of this group are built with Swedish wheels that cause vibrations as previously explained. Type A thus corresponds to a high operability even if the maneuverability is not maximum. This device therefore is the best choice for physical therapy indoor. A home use of a SW requires high maneuverability, and type C appears to be the best type for this. If Swedish wheeled devices are excluded, devices such as ORTW (Omnidirectional Robot-Technology Walker)[61] are dismissed, only devices such as PAMM (Personal Aid for Mobility and Monitoring)[25] fit the needs thanks to their ASOC-type wheels.

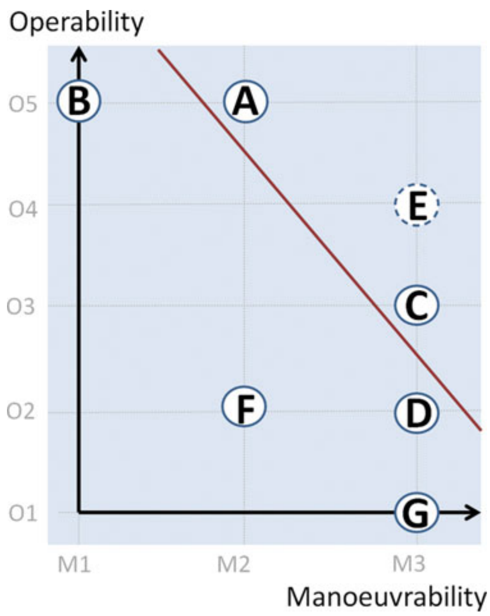

Fig. 4. Classification of the different families of smart walkers according to operability and maneuverability.

This analysis shows that a compromise has to be found between all the criteria : the SW has to be large to be stable but not too large so as to be able to move in narrow spaces, the power transmission has to be simple, reliable and well operable but this simplicity can decrease the degree of maneuverability of the device, leading to discomfort and even a rejection of the device by the user. Mobile base is not the only issue impacting the design of a SW and we will discuss issues about support in the following part.

3. Supporting and Stabilising the Patient

The primary aims of classical walker prescriptions are improvement of the balance and lateral stability of the patient by increasing the support base and relieving of some of the weight borne by lower limbs. After identifying the needs, different methods are applied in order to choose the most appropriate walking aid.[38] However, we can notice some constant principles which are, in order of preference: preserving the safety of the "user-SW" partnership, limiting the alteration of the patient's posture and walk pattern, and enhancing walking speed. In this part, these three principles are used to evaluate the proposed solution for supporting and stabilising users. The solutions are organised in three subsections to select the most adapted support surface, strolling control and loss of balance management methods.

3.1. Select the support surface

The selection of contact surface between users and SWs is essential to support and stabilise users. Different solutions have been proposed. They are classified in Fig. 5, according to the anatomic part of the user in contact with the SW and the type of contact.

3.1.1. Handles. The use of handles is the simplest and minimal-contact solution, found in half of the SWs. For stabilising with the handles, the user need to have enough strength in arms and forearms to control his/her body in applying efforts to the handles.

The handles can belong to the coronal plane, the sagittal plane or be in an intermediate position (see on Fig. 5). The coronal plane handles are the easiest means to push the walker; whereas the sagittal plane handles are better to lean on the walker and drive. The orientation of the handles trades off between push or drive functions as presented in Fig. 6.

If, in addition to give confidence to the user, the purpose of the walker is to support him, sagittal plane handles appear to be more appropriate. The difference between sagittal plane handles and intermediately positioned handles according to support has not been extensively studied so far. When

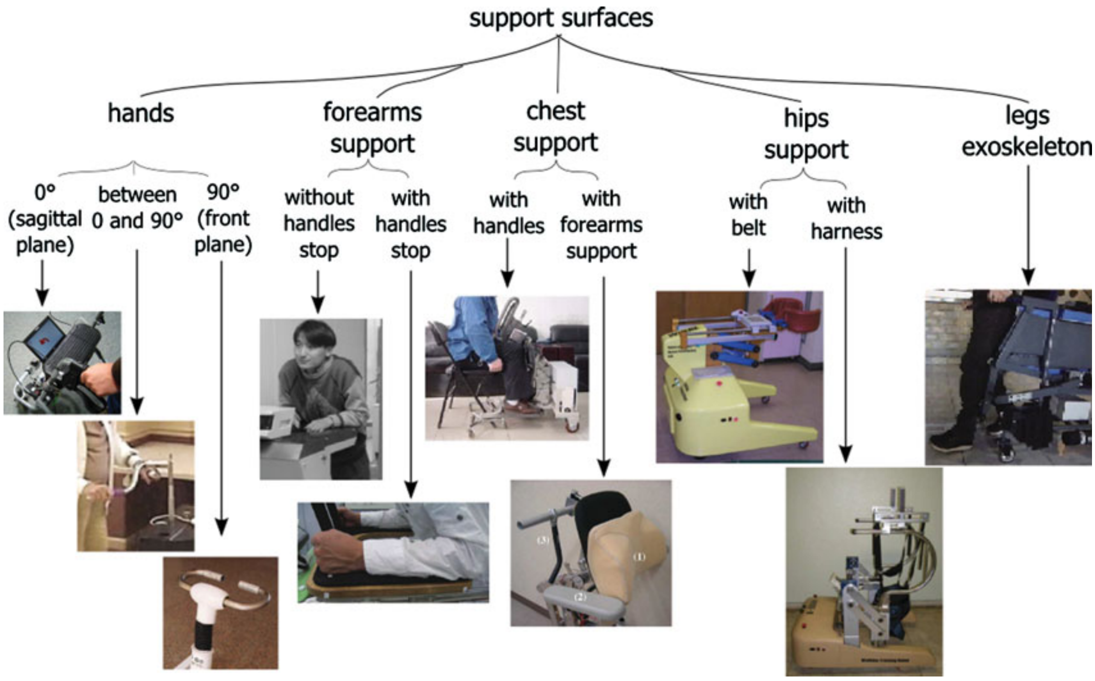

Fig. 5. Classification of the different support surfaces with images of different existing prototypes.[33,44,51,56,87,94,103–105]

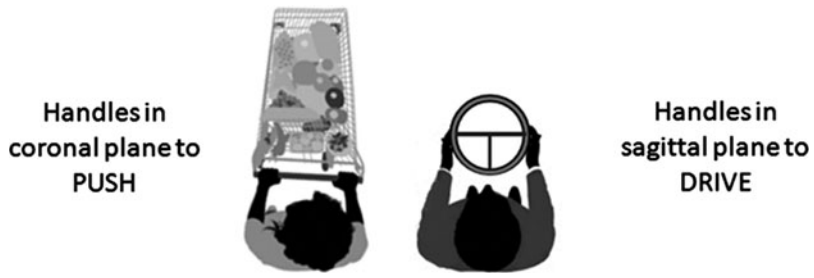

Fig. 6. Handle directions and their functions: push or drive.

the user/SW contact is established with handles, the upper part of the body is well adapting and lower pertubations on the posture or the walk pattern are noticed.

3.1.2. Forearms and chest support. The two following supports (forearm and chest) increase the contact surface between users and SWs (see on Fig. 5). Although the users are more supported and stabilised, they are also more constrained which causes discomfort and bad acceptability of the device. Consequently, this kind of support is required for people that have frail upper limbs and/or trouble of grasping as in case of osteoarthritis.[39] They are also used to avoid anterior tilting posture of users with Parkinson disease.[40] In case of a possible grasping (even a weak grasp), handles are added to the forearm support to improve user stability and sense of control. That's the reason why handles and forearm support are also added to chest support.

3.1.3. Hips and legs support. Hips support[37] and legs exoskelton[38] have been developed but remain rare for SW. They are recommended for users with weakness in legs and who cannot correct their posture using only the upper part of their body. The support can be even more complete[41,42] for paraplegic users for example. These solutions are very constraining and need an assistant for being setup. They are more appropriate for rehabilitation purpose.

Once the choice of the most appropriate support for the application is defined, the surface of contact itself can be improved. Indeed, padded handles or ergonomic handles[43] can reduce the difficulty of grasping and so improves the comfort for the user. Likewise, chest supports have to be designed with a comfort goal.[44]

3.2. Strolling controls

For providing a safe support during the use of SWs, especially when strolling, the device has to stay near the user. In order to synchronise motions between the SW and the user a strolling controller is implemented. This controller enables the SW to go ahead, turn, go back or stop according to the user decision. It is a lower level control that receives orders in robot operational space. The inverse kinematic model of the SW is as a mobile robot model, and the associated controller is the same as the ones used in mobile robot field. An interesting different approach is proposed by Chuy *et al.*[45] where the controller regulates the position of the centre of rotation of the SW in order to follow an expected path.

User data are required for the strolling control. Two solutions are proposed to extract them: the study of interaction forces and posture measurement (mainly feet positions). The interaction forces solution provides information to both the user and the device. This solution can lead to shared decisions[46–51]. The shared decision is generally done with admittance controller. This controller uses the input force to update the speed of the robot. The device provides power that reduces the apparent weight of the SW in order to be appropriate for a frail person. For users who do not have muscular failures but need an orientation help because of cognitive issues (e.g. memory issues or disorientation symptoms), a simpler and safer approach has been introduced[26,52] which is a passive approach of admittance (the controller drives only a brake). The braking strategy provides an acceptable navigation help. The interaction port comprises handles in most of the cases. Sometimes, it can also be arm rest[11,22,50,53] or hip support.[51] In order to decrease the physical workload of the user,[54] proposed heuristical rules as a possible alternative to admittance control.

Measuring positions of feet is a part of postural observation sensing that is used in strolling motions. The device estimates the actions that have to be performed thanks to the motion and the postural state of the user. Hirata *et al.*[55] show how to describe the posture of the user based on the relative positions of feet and trunk. Another postural detection, implemented by Lee *et al.*[22], gets the directions from the position of the two feet. Their originality is to be able to identify discrete wanted motions (forward, backward . . .) instead of continuous as in other works.

The sensing actions can be fused for obtaining more accurate or robust information. The fusion of iteraction forces data with posture sensing[11] or with tactile sensing[56] have been explored.

3.3. Methods for managing loss of balance

Different methods have been proposed for avoiding falls while using SWs. Falls of elderly people occur mainly in the anterioposterior plane during intentional movements.[57] Thus, available studies focus on loss of balance in the forward/backward direction. The risk of imminent fall is detected through loss-of-balance indicators.

Three types of loss-of-balance indicators have been proposed. These types are: (1) interaction forces between walkers and users, (2) users' posture estimation and (3) users' kinetic estimation. The first type of indicators relies on the assumption that the user tries to make it up on the handles of the SW if he/she feels a loss of balance. As an implementation of this indicator, Bülher *et al.*[37] detect too high pushing forces in the vertical direction as an indicator of possible imminent fall. Likewise, Martins *et al.*[58] use as an indicator the horizontal component of the force in backward direction: a too high force indicates that the user is likely to fall backward. This first type of indicators relies on the assumed reaction of the user. They tend to produce a large amount of false positive detection.

The second type of indicators, based on the estimation of the user's posture, aim at detecting hazardous posture that can lead to fall. The implementation of a such indicator was done by monitoring the relatives distances between user's legs and the walker.[59,35] Assuming that the user's hands stay on the handles, this indicator gives postural data that can evaluate the safety of the user's posture. This indicator could be improved by relying on a body model[55,60] in order to be closer to balance studies. These indicators avoid human reaction related false detection that can be seen with the first indicators. Nevertheless, walking and falling are dynamic processes and other methods that are not purely static could lead to better results (especially for earlier detection).

The third type of indicators, kinematic indicators, is used by Nejatbakhsh *et al.*[61] in order to avoid falls. They rely on the assumption that a frail user cannot use a SW with high speed safely. So, they

Table I. Obstacle sensing technologies on the studied SW.

Technology	References	#
Ultrasound	10, 66, 104, 23, 106, 72, 59, 107, 35	9
Infra-red	10, 46, 32, 67, 23, 106, 35	6
Laser Range	70, 99, 55, 61, 49, 31, 26, 75, 108, 109, 69, 59	12
Stereovision	72	1
Camera	72, 59	2

increase damping when the velocity of the SW is too high. In this example, kinetic data is used but a too high velocity of the walker is not specific to imminent risk of falling. So, this indicator is relatively constraining for the user that cannot excess a fixed speed.[62] propose to use XCOM (eXtrapolated Centre Of Mass) to take the COM into account but also the COM speed. This indicator helps making earlier and more specific detection. However, accurate thresholds bounding the safe area for this indicator remain unknown so far.

Available studies about loss of balance management recommend in general to stop the SW when a risk of falling is detected. They propose to do so because correcting patient's motion seems too hazardous. However, Geravand *et al.*[62] propose a system of articulated arms that applies efforts on the user in order to help him/her recovering balance. Nevertheless, further experimentation is required for validating this method.

4. Overcoming Cognitive and Sensory Deficits

SWs can be used for addressing some cognitive and sensory deficits. The first addressed sensory deficit was vision.[10] When the user is lacking of visual sensing the system has to be able to deal with situations that are hazardous for the "user-SW" partnership. For this purpose, obstacle avoidance strategy are implemented on SWs. The second addressed deficit is the lack of orientation. This can be caused by cognitive reasons (e.g. Alzheimer's disease) or by sensory disease (e.g. blind people). In order to address these issues, a navigation system can be implemented on SWs. Then, the SW is willing to provide feedback to the user and because of the wide spectrum of sensory deficit in ageing population many feedback communication have been explored. In addition, the monitoring of users' behaviour could improve rehabilitation and clinical follow-up.

4.1. Obstacles avoidance methods

Using SWs in concrete settings requires some safety needs. The assistive device should not either hurt someone or hit objects neither go in directions that could be dangerous for the user or the system (e.g. stairs). The system should at least be able to stop in such a situation in order to keep the user safe. As presented in Table 1, most of SWs implement a mechanism in order to deal with obstacles. The developed mechanisms are of two kinds: stopping and avoiding. The stopping mechanism is implemented in mobile robots that use proximity sensor like ultrasound. This low price technology has the ability to sense obstacles at short distance (lower than 1 m) with a relatively reliable precision.

The avoiding strategy is combined with the walking action. Many way to mix avoidance have been developed. Three sensing technologies are generally used: Infra-red distance arrays, 2D lasers and depth sensors. IR arrays are often used combined with ultrasound sensor[10] that allows a sensing in two ranges of distance: for a small distance (less than 1 m for ultrasound) and for a longer distance (between 1 m and 2 m for Infra-red sensing). This combined system allows a visibility of the obstacle that can be used in order to apply avoiding strategy based on moving along the obstacle until the robot has its target not obstructed, which is called the "Bug algorithm".[63] 2D laser distance sensors are used in the later SWs because of the cost reduction of this technology in the last years and the reliability proof that this technology has shown.[55] Camera-based solution is the least used technology. A stereo-camera combined with a front camera is used in "Hitomi" prototype[64] for outdoor use. The small number of implementation of these technologies may be explained by their poor reliability when luminosity changing.

4.2. Navigation help methods
The navigation help provides information for moving from a starting position to a goal position. In order to achieve navigation help, the system requires three subsystems: map, localisation and planning.

The map subsystem rationale is to move in all the directions, to identify obstacles (walls, table. . .) and to record them in a database. Different strategies exist for mobile robot but none of them are specific for helping the elderly.

The localisation system is strongly connected to the mapping subsystem, as it positions the device in its environment. For SWs, sensors are usually placed in front of the device, except when an omnidirectional camera is used.[31] Using SWs indoor enables specific localisation systems as for Spenko *et al.*[21] They put identifiable target images in the ceiling of each room for supporting localisation. Another solution consists in integrating passive RFID tags in mats for key locations.[65]

The planning system aims at providing a path between two positions in relying on the whole map.

When a navigation system is implemented, some feedback is required for the user. This system is mainly used for users that cannot see well or that can be disoriented.

4.3. Human-robot communication channels
Communication between users and SWs is bidirectional.

4.3.1. From walker to user communication. The vision sense has been explored by using screens[23,49,59,65–69] to provide localisation information (e.g. the position of the user on a map). The main difference in these communication media is the interface ergonomics (e.g. size of the icons, combination between written instruction and visuals[65]).

Directions and positions information can also been transmitted through hearing sense with a voice synthesis module.[70–73]

The touch sense could be used as a direct physical feedback in some cases of cognitive or sensory deficits. The system could be a fully automated motion[18,64,69,74] or a guiding strategy that modifies the user current trajectory for going to the targeted direction.[19,69] One experience of haptic feedback for navigation has been tested.[75] Another approach is done by Siemens Robot[76] with vibrating braces wored by users on forearms in order to give directional information. The use of braille for blind people has been suggested by Kotani *et al.*[64]

4.3.2. From user to walker communication. The least intuitive way to communicate from user to SW is the simplest one in a technological point of view: the button.[77,78] In addition, joysticks can be used[19,75] as well as tactile screen.[59]

Many feedback devices have a weakness. They want to provide support for people that are not able to find their way but also users must be able to use computer technology. These conditions are rarely met in one person. As a consequence, the core research with such devices are the interface ergonomics. Other researchers have explored the use of verbal medium announcing the actions of the SW.[65,72] The announcement of the directions increases the acceptance of the SW action even when the robot moves autonomously.[72]

4.4. Monitoring of physiological parameters methods
The knowledge of the users' activities and health monitoring should have a lot of benefits for both clinicians and users. In this part, relevant parameters that can be monitored and their potential uses will be examined.

First, monitoring physiological parameters can be used for short term applications, mainly for emergencies detection. Monitoring heart rate can enable to warn of an hazardous situation.[79] For this monitoring, different sensors can be used such as pulse sensor in the handles[79] or with photoplethysmography principle.[80]

Then, monitoring physiological parameters can also be used for middle term applications, especially for rehabilitation. The system could inform users to correct themselves or to encourage exercising.

Observing long term changes provide useful data for health and wellness monitoring.[81] Indeed, it can help therapists for early detection of disorders, for assessment of treatment efficiency and for rehabilitation process follow-up. Such uses rely on the estimation of the posture and on the level of activity from different sensors embedded on SWs (e.g. force sensors,[82] camera[83]); typical features of the walk can be extracted.[84]

The posture is estimated with precise parameters as presented in the two following examples. Haussdorff *et al.*[85] showed that stride-to-stride variability is a good parameter for predicting the tendency to fall and Spenko *et al.*[21] use power spectrum of the walk events for evaluating the symmetry of the walk. Asymmetry can alert about minor strokes or injuries and can also be an adapted parameter to follow rehabilitation process after such a kind of injuries.

Moreover, assessing the level of activity could be provided by monitoring the forces applied by the user and the speed of the device.[21] More precise measures have been proposed[68,86] with a classification of the different daily activities of the user. This information can help the therapist for users' independence assessment. These data can also be used to evaluate the consequences of certain medical choices and to propose activities that fit with the needs of the patient (e.g. changing for more motivating exercises). More specific detection methods for completing the estimation of the level of activity have been proposed as a seat usage monitoring.[80] Indeed, contextual and multi-sensors processes seem more adapted to achieve an efficient activity level detection.

5. Adapting to Daily Life Transition Phases

In order to use their SW, users need to access it. Otherwise, users would need assistants for having the walker in a correct position and for standing up. In order to help the transitions between activities, different solutions have been proposed. These solutions can be classified in two categories : those that do not need contact with the user (as calling the SW from its docking station) and those requiring contacts (as the STS assistance).

5.1. Initiation and interruption of the use of smart walkers

Two main reasons can lead users to dock their SW. They can do it at the end of the day in order to charge it or at any time of the day in order to free some space around them (e.g. in house, in a restaurant). Likewise, users can desire to call their SW after a docking. Clearly, in order to be automatic, the functionalities encompass obstacle avoidance and navigation that have already been discussed in Section 4.

Navigation from one room to another has been implemented on SWs[59] with similar techniques as for companion robots. In these implementations, users call mainly SWs with remote devices.[59,70] Tackling voice calls is challenging (noise and ageing voice) and can decrease the acceptability level of SWs. For docking actions, classical navigation is sufficient as the docking point does not move in the house.[74] However, for calling the SW,[20] the system requires more precise approaches.[87] Indeed, if the SW comes to users but stay slightly too far or if it is not well oriented, the user can fall while trying to catch it. Yoo *et al*.[87] proposed a multi-modal assistance (sound localisation and a face tracking) in order to manage getting closer. Even if this implementation is limited in crowded spaces, it seems very promising for adapting the position of the user.

5.2. Sit-to-stand assistance methods

Standing up is one of the most critical issues when using SWs. This transition concerns most of SW users and is not environment-dependent. Many structures and controls have been developed in order to assist the STS motion. Some designers propose a braking system to ensure a support that does not move for the user,[88] others control only the forward direction of the SW in order to pull the user[88,89] and some others implemented more complete help with more complex movements.[90] The solution of only pulling users is not ideal because it does not fit with natural STS. However, this solution is simple and offers a first solution for assisting users. Available prototypes on which this control is applied are connected to users with handles. Indeed, constraining forearms in one direction is very uncomfortable for users.

The STS motion can be first studied only in the sagittal plane with a symmetry simplification. With this hypothesis, if users are linked with SWs with handles, commanding the contact point in two directions independently is sufficient to be able to achieve all the possible trajectories. This point can be controlled in only one direction.[88,89] By adding only one actuator in the upper part of SWs and combine this new motion with the forward motion, an infinite number of trajectories can be provided[20,91] in order to assist the STS motion.

In order to increase the provided help for users, some designers realised forearms or chest supports.[33,37,50,76,90] For this kind of support, three dimensions have to be considered (the position of one point and the orientation of the support surface). For being able to execute any trajectory, two degrees of freedom (DOF) are needed in addition of the mobile part.[90] Keeping the orientation of the arms of the users constant simplifies the problem: only one DOF is required.[76,92]. However, this method decreases the comfort of the user as it will be seen later in this part. Three DOF,[50] and even six DOF,[33] can be added to assist the STS. Even if these methods could uncouple the forward and the STS motion, resulting systems are more difficult to control. To the best of our knowledge, nothing has been published for the control in STS of the prototype presented by Xiong *et al.*[33] It has been shown that by increasing the complexity of the device, a more complete service can be provided to users. Especially, more trajectories can be proposed but the issue of selecting the best trajectory for each user remains open.

Former research explores the best trajectory elaboration through two main approaches. The first one evaluates different trajectories on subjects and selects the best one according to a criterion and the second one imitates the physiotherapist trajectory. In general, the first method is perceived as a preliminary work on STS motion and is used to test the methods and the criterion in order to assess the quality of trajectories. The criteria used to select the best trajectory are the displacement range of the Centre Of Pressure (COP),[50] the joint torques mean and maximum values[50,92] and the ratio of the torque joints of hips and knees[76] obtained with force plate and motion capture systems. The goal is to fit the unassisted movement characteristics of a healthy subject, reduce the torques needed for standing up and maximise stability. Nevertheless, these studies rely on only one or two subjects and so general rules are difficult to extract from these results. However, two studies[50,76] highlight the same property: inclining the arm support leads to a more stable and natural motion.

Two studies have followed the second approach in order to found the best trajectory to implement on their SWs. Force plates provide interaction forces and posture evaluation, trajectories and estimated joint torques. Trajectories used by therapists are different for each subjects. For adapting easily to all users during STS, a parametric solution was proposed.[34] Sitting-down is usually considered as a reverse STS but Chugo *et al.*[17] studied the required trajectory for sitting comfortably and found differences between reverse STS and sitting motion (for example, less inclination of the forearm is needed when sitting). The same team has proposed to assist STS not only with a following of trajectories but also with force control in order to prevent a too high knee torque.[90]

When the mechanical design and the control of STS is done, the willing of changing of state remains to be determined. Hirata *et al.*[88] used the distance between the SW and the trunk for detecting in which phase the user is. Efforts in the handles can also be used to start the STS motion.

Additional functionalities have been proposed for supporting the STS transition. Indeed, for elderly people, backward motion is not easy and go backwards until reaching the right position to seat is a dangerous task. Chugo *et al.*[44] designed an assistance for approaching the seat in a more secured way with an automatisation of a part of the approach task. More simply, the possibility to seat on the walker to take a rest in a walk can also decrease the risk of falls and has been used for some SWs.[36,76,93–95]

6. Evaluating of Smart Walkers

When developing a SW, designers regularly evaluate their prototypes. During preliminary steps, experiments are performed with researchers using their own device or with healthy subjects in laboratories. These first observations are used in order to design: the controller;[50,96,97] the navigation functionality;[32,61,89] the path following functionality;[98] the STS assistance;[99] some usability criteria such as stability,[15] with healthy elderly people. The healthy young subjects can wear special equipment to limit mobility and thereby be closer to the final user behaviour.[44,78] Even if experiments with healthy subjects are initially needed, tests with final potential users are necessary. Effects of ageing on sensory and cognitive functions and the pathologies for which the walker is needed can hardly be replicated by healthy subjects.

Potential final users can be solicited early in the development process of SWs. Before the realisation of the prototype, users may be questioned to determine and quantify the performances the SW has to reach. They can provide information about their daily needs and thus participate in the elaboration of the use scenario.[10] Users can also take part in measurement experiences with caregivers to determine the ideal help that the SW should provide. For example, for collecting data in order to determine trajectories that should be followed by handles during a STS assistance, experiments were conducted on 17 elderly subjects using walkers in the Service de Gérontologie l'Orbe de l'Hôpital Charles Foix, AP-HP, Paris.[100]

When the prototype is built, quantitative measurements to assess short-term efficiency of SWs are used. SWs are tested in the application for which they were designed (potential final users and their use cases). For example, Graf[19] used, for experiments with the elderly, a path running through their usual environment, including lifts, narrow corridors and access ramps. A gait analysis (e.g. walking speed, step frequency)[101] is computed with the different available walking assistance (SW, traditional walkers, ...) to evaluate the prototypes.[10,18,19] These experiments serve to validate different functionalities. For example, experiments for evaluating the guidance capabilities of Care-O-Bot[19] highlighted the weakness of the SW. This weakness was mainly linked with the non-omnidirectional structure that created difficulties to maneuver and with the limited speed of the SW. Some functionality evaluations can require additional measurements. The variability of the steps was added to classical gait analysis[18] to assess the effect of CAIROW on specific walking difficulties of users with Parkinson disease.

Pure quantitative evaluations are incomplete because they do not take in account the level of satisfaction of the potential final users even though they are the best suited to evaluate and influence for the product development. In order to assess the satisfaction of users, designers proposed informal or formal questionnaires. Informal questionnaire was used for satisfaction evaluation by Morris *et al.*[67] with four dwellers. This kind of questionnaire can contribute early in the design phase, but also in the middle phase of development and subsequently, at the end of the development[70] with staff and older adults. Formal satisfaction questionnaire were also used.[22,54,102] The same type of questionnaire was used by Frizera Neto *et al.*[102] with three groups of patients (classified according to levels of disability using the Walking Index for Spinal Cord Injury). The eight patients involved in this study walked 10 m in a straight line, turned back and returned to the starting point. The ease of manipulation of the SW for users was evaluated in four situations : motion start, straight walking, performing turns and motion stop. Two additional questions about security and comfort completed the questionnaire.

The most complete evaluation we found was that of GUIDO, which was performed throughout its development.[10] A final evaluation of the commercialised product was conducted[47] with 17 final potential users (elderly people with a visual impairment). The SW was evaluated quantitatively. The completion times on a same path with usual difficulties encountered by the users were measured in three cases: an assisted walk with Guido, an assisted walk with a third party and an assisted walk with the Assistive Mobility Device, designed at the Atlanta Department of Veterans Affairs Medical Centre. The SW was also evaluated qualitatively. Subjective mobility questionnaires were proposed before and after the experiments.

As far as we know, no study proposes a long term effect study. This kind of study requires two groups of users: one that uses the SW and one that uses classical walking aids. The number of users that would be needed is one of the main difficulties. Indeed, studies are in general presented with small groups (six people using traditional walking aids[19] and seven people with PD on two days[18]). Nevertheless, long-term studies are required to assess SW efficiencies. The application that seems the easiest for evaluating long-term effects is rehabilitation after hip fractures. Indeed, this pathology is common and rehabilitation allows simple measurement for assessing efficiency (occurrence of falls after one and three months in clinical following, mean progress in walking speed).

To summarize, qualitative and quantitative standardised tests have to be performed with the involvement of the potential final users in order to evaluate SWs. These experiments are based on clinic evaluation tests using physician's assessments. These evaluations should allow to compare results obtained with different robots and could help the community working on SW projects in finding an objective reference in order to appreciate progress.

7. Conclusion

This article proposes a method for developing each module that is required for designing SWs regarding to their application.

SWs are mobile robots. Many mobile structures are available in the literature but the classification we propose highlights two kinds of SWs. If the application takes place in crowded environments (e.g. home), we recommend using SWs with ASOC type wheels, specifically for their omnidirectionality and ease of movement. However, if the application is in vast environment (e.g. for rehabilitation exercises), structures with two fixed wheels close to the user seem more adapted, as simplicity takes priority over omnidirectionality for these applications. This method appears to be reasonably stable since mobile robotics issues are well explored. At a first glance, possible advances on spherical wheels may later change the conclusions of this study but not the method.

The second category of modules aims at supporting and stabilising the user. This module requires to implement three modules: a support surface, a strolling controller for lowering the risks of falling and a module for managing loss of balance. For the support surface, our selection method is based on three aspects in accordance with clinician prescriptions. First, the support surface should secure users, while maintaining user involvement in walking. Secondly, the support surface should limit physical constraints raised by the module. Finally, the support surface that maximises the walking capabilities is preferred. Thus, the selection of this module mainly depends on the patients' pathologies. When developing support surface, we recommend to perform extensive communication between the user and the medical staff for better shaping and allocating the different support surfaces. For the strolling control module, many solutions are still in development. To that extent, we do not bring a conclusive selection method, which would be too early. Consequently, even if we classified the existing methods for achieving this goal, no method for choosing it is presented. As a guideline, force control is used in most of the SWs. For the loss of balance management module, in spite of recent progress for detecting intentions, available methods are insufficient for integrating the selection of this module within a streamlined method.

The third category of modules aims at handling cognitive and sensory deficits. These deficits are overcame mainly by four modules: obstacle avoidance, navigation help, communication between users and SWs and managing physiological parameters. Our method propose to consider first obstacle detection, which is required for obstacle avoidance and navigation. This detection relies mainly on the selection of environmental sensors. We recommend to combine existing obstacle detection technologies in order to adapt to multiple distance ranges. When navigation module is required (for memory issues), the second step is to select technologies to establish map and localisation. These choices are made according to the environment (e.g. possibility to put RFID in carpets or ceiling). The third step of our method consists in selecting the communication means between users and SWs (e.g. for warning about hazardous area). We recommend to prioritise means that do not require a lot of attention from users as haptic feedback. Nevertheless, especially for navigation, the user need to access consciously to the direction and also to give orders to the SW. In such a case, communication means should be chosen according to the communication capabilities of users (e.g. Braille for blind users). The last step of our method consists in determining which data to gather according to the clinical goal (emergency warning, monitoring rehabilitation progress, preventing falls).

The last category of modules aims at supporting transitions when using SWs: calling the SW and switching from sitting to standing position (STS motion). Our selection method for implementing the calling module is based on the environment (e.g. crowded, visual obstruction) and communication capabilities of the user (e.g. sufficient spelling, raising an arm). The STS module, in order to assist the 2D motion of users, relies on the execution of 2D trajectories of support surfaces. The first step of our method consists in selecting the mechanical design that enables adequate trajectories. This selection is based on the required number of DOF (itself induced by the choice of the support surface module). The second step reposes on the selection of the trajectory to perform. Nevertheless, we cannot provide further answer because no experimental comparison between the different trajectories is available.

Finally, we propose a method for evaluating SW as a whole. In particular, we detail a three-step process: first, evaluating the SW with healthy people; second, evaluating the SW with users (both qualitatively and quantitatively); third, evaluating long-term effects of the use of this SW (e.g. better recovery with a SW against a conventional walker).

This article proposes a method for assisting designers when making choices throughout the conception of SWs prototypes. We decomposed this method for each modules that composes SWs.

Despite of limitations raised by quickly evolving parts of the field, this method offers clear guidelines for rationalising choices made in the development of SWs.

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