Chapter 2 Recent advances in mobility assistive devices for stairs or curbs

This Section provides an overview of recent advances in mobility assistive devices available for curbs or stairs at the time of writing. The coverage focuses on the curb or stair climbing ability of the devices.

2.1 Curb assistive mechanisms for wheelchairs

(a) Additional wheel illustration (b) additional wheel photo (c) Curb catcher illustration

Fig. 16 Curb assistive mechanisms

Photo courtesy of Shoprider (b)

- **Features**
  - Raises the curb negotiating ability of a wheelchair's front wheels
  - Retrofitable to a wide range of manually propelled and powered wheelchairs
  - Low cost
  - Light weight

- **Negative points**
  - Increased frontal area required for turning (additional wheel only)
  - Cannot operate backwards (curb catcher only)
  - Not available for or compatible with all types of wheelchairs

- **Comments**

At the time of writing a number of curb assisting devices are available for manually propelled and powered wheelchairs. One such device provides additional wheels mounted on the front wheel caster assemblies [17]. The additional wheels are positioned a little forward and higher than the wheelchair's casters so as to hit the curb first and raise the front of the wheelchair and enable easier negotiation of curbs. This is illustrated in Fig. 16(a) and depicted in Fig. 16(b). Another device is the positioning of a hinged curb catcher as shown in Fig. 16(c). The curb catcher hits the curb and rotates as shown by the dotted line resulting in lifting the front of the wheelchair enabling negotiation curbs.

2.2 Curb capable powered wheelchairs and mobility scooters

(a) 150mm curb wheelchair (b) 120mm curb 4WD scooter

Fig. 17 Curb capable mobility assistive devices

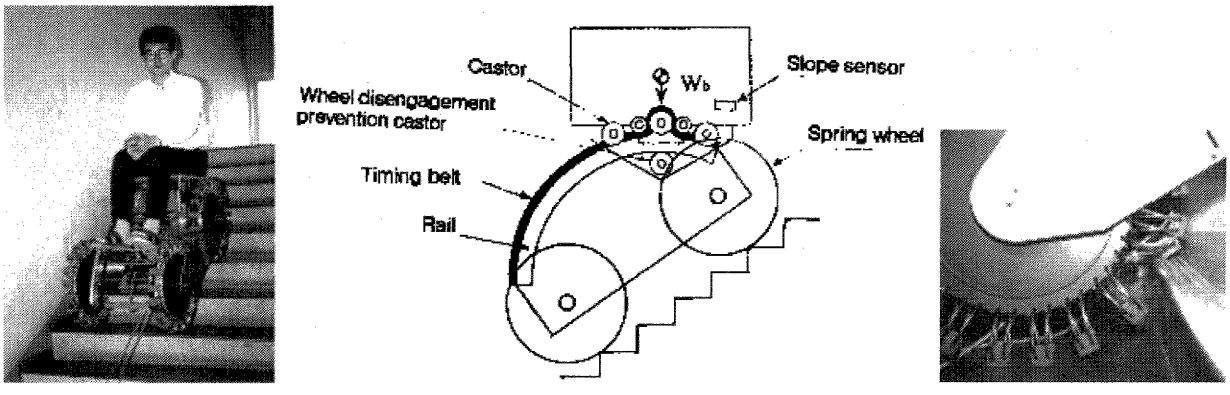
Photos courtesy of A1 mobility (a), and Serio-Japan (b)

- **Features**
  - High curb negotiating ability (150cm powered wheelchair/ 120cm mobility scooter)
  - High level of mobility in most environments
  - High level of stability (cf. manually propelled wheelchair)
  - Easy to operate (mobility scooter only)

- **Negative points**
  - Large turning circle (mobility scooter only)
  - Joystick operation difficult (powered wheelchair only)
  - Heavy (therefore very difficult to assist with stairs or van entry without special equipment)

- **Comments**

Persons with limited upper limb ability have traditionally used such as a fully powered wheelchair, however the task of controlling a powered wheelchair is relatively difficult and research continues toward simplifying this task refer to [18]-[21]. The powered wheelchair shown in Fig. 17(a) [22] is designed to negotiate curbs up to 150mm, the front wheels (anti-tip device) are adjustable in height and are raised when curb negotiation is required. Mobility scooters such as that shown in Fig. 17(b) [23] have become increasingly popular for both elderly and disabled persons, part of the reason for increased popularity is they are easier to control compared to the powered wheelchair and seem to have gained greater acceptance by the public compared to the powered wheelchair. While both powered wheelchairs and mobility scooters provide excellent general purpose mobility their weight makes assistance with stairs or van entry without special equipment very difficult. A wide variety of lifting mechanisms are available, however at significant cost and tradeoff in terms of space etc (refer to Sections 1.6.2 and 2.8).



(a) TAQT wheelchair (b) TAQT principle of operation (c) TAQT spring wheel close up

Fig. 18 Terrain-Adaptive Quadru-Track (TAQT) based wheelchair

Photos and illustration courtesy of Shigeo Hirose

A 4WD mechanism provides improved curb negotiation compared to 2WD (2 wheel drive) operation, however a 4WD mechanism is not well suited to stairs for 3 fundamental reasons. Firstly the lack of necessary traction, secondarily the change of vehicle angle during the stair climb reduces the vehicles stability to unacceptably low levels and finally in the case of a vehicle propelling a person such as a wheelchair the seat angle should ideally remain relatively constant. A prototype mechanism dealing with all of these issues is outlined in [24]. The Terrain-Adaptive Quadru-Track (TAQT) based wheelchair prototype is pictured in Fig. 18(a), the principle of COG modification illustrated in Fig. 18(b) and a close up of a wheel (spring loaded) gripping a stair edge is shown in Fig. 18(c).

2.3 Track based stair-climbers

(a) Autonomous stair-climbing wheelchair (b) Stair-climbing wheelchair transporter

Fig. 19 Modern single track based stair-climbers

Photos courtesy of Hospimedica group

- **Features**
  - Stair-climbing ability
  - Autonomous stair-climbing possible (autonomous stair-climbing wheelchair only)
  - Suitable to most outdoor stairs and some indoor stairs
  - Simple operation (cf. non-track based stair-climbing mechanisms)

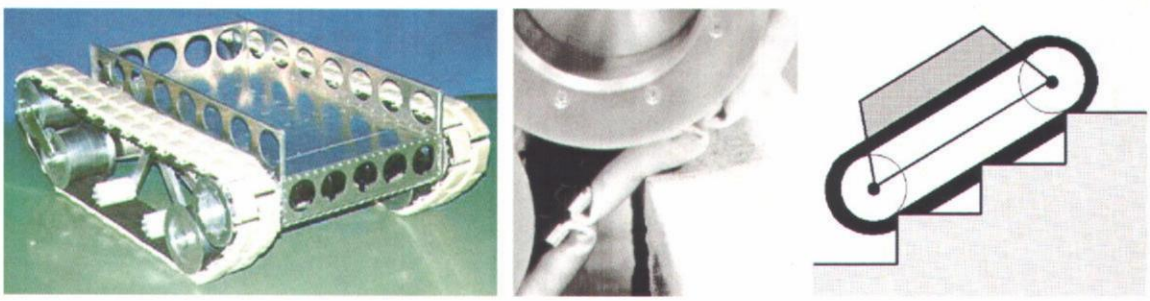
- Provides stair-climbing ability for standard wheelchairs (transporter only)
- Provides for general purpose off stair operation (autonomous stair-climbing wheelchair only)

- **Negative points**
  - Must climb stairs backwards
  - Special mechanisms required for off stair operation and changing to and from stair-climb angle
  - Non slip mechanism required when on stairs (tread/ knobs), asynchronism between stair edges and tread/ knobs results in high non linear pressures exerted on stair edges
  - Unsuitable for most indoor stairs and some outdoor stairs
  - Heavy (cf. standard power wheelchair - autonomous stair-climbing wheelchair only)

- **Comments**

Tracked climbers are dealt with in more detail in Section 4. A modern single tracked fully autonomous stair-climber and powered wheelchair is shown in Fig. 19(a) and a platform used to carry a wheelchair and user up or down stairs is shown in Fig. 19(b) [25]. An older technology single track stair-climber is shown in Fig. 62 (powered stair-climber – free wheeling on the flat) and Fig. 64 (tracked stair-climbing wheelchair transporter operating at a station in Japan). The central advantage of the use of tracks is the independence or robustness regarding the type of stair or surface being negotiated. Disadvantages of track based operation include the high pressure exerted on the stair edges therefore limiting use to stairs with appropriately robust leading edges. An anti-slip mechanism is required while on the stairs and a mechanism is required to ensure the device changes to and from the stair angle in a controlled manner at the top of stairs.

Regarding the most fundamental track based problem, that of the high pressure exerted on the stair edges a deformable track has been proposed and modeled in [4]. The track consists of deformable or hysteresis blocks configured as shown in Fig. 20(a). The principle of operation is shown in Fig. 20(c), namely to spread the stair edge load over a larger area as well as inherently provide a means to prevent slipping that is not reliant on the track tread (knobs) synchronizing with the stair edges. This compares with a regular wheelchair track as depicted in Fig. 58(a), illustrated in Fig. 58(b) and discussed in Chapter 4.



(a) XEVIUS tracks (b) XEVIUS track close up (c) XEVIUS track principle

Fig. 20 Xero-Viscous Upstair Service (XEVIUS) deformable tracks

Photo and illustration courtesy of Shigeo Hirose

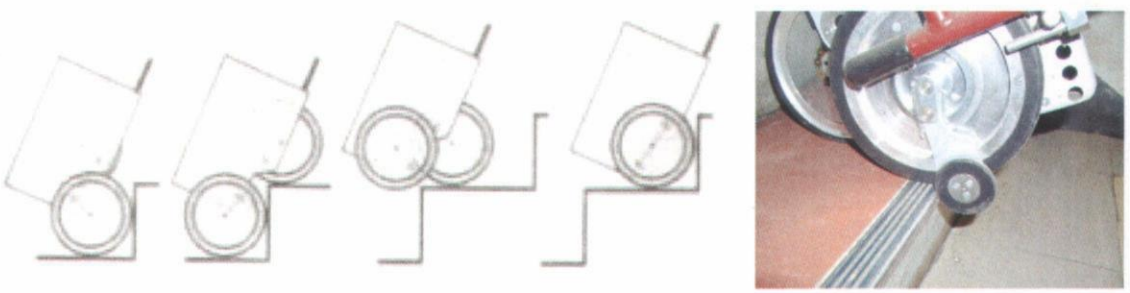
2.4 Lightweight wheelchair stair-climbing attachments

(a) Stair-climb mech. (b) Mech. attached to wheelchair (c) Stair-climbing operation

Fig. 21 Scalamobile – stair-climbing attachment

- **Features**
  - Stair-climbing ability
  - Suitable to almost all stairs (max. step height up to 25cm Scalamobile/ 21cm C-max)
  - Compact
  - Uses existing wheelchair – no transfer required (Scalamobile only)
  - Lightweight (˜ 25Kg plus wheelchair Scalamobile/ ˜ 32Kg total C-max)

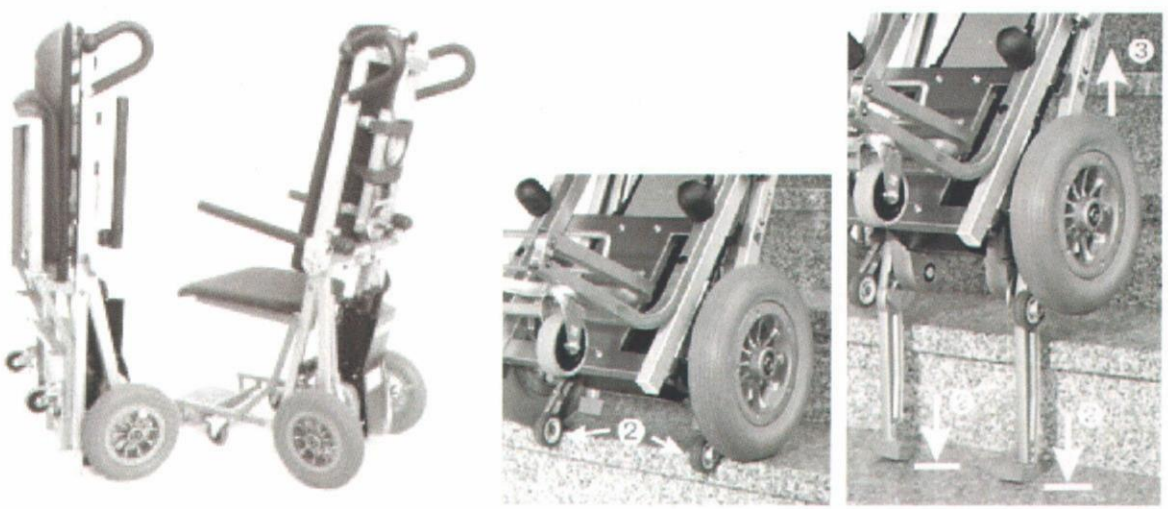
- **Negative points**
  - Requires special instruction regarding usage (Scalamobile only)
  - Dedicated assistant operated wheelchair – transfer required (C-max only)
  - Orbital motion tends to be uncomfortable for passengers (Scalamobile)
  - Auto-brake mechanism does not suit roughly surfaced stairs



(a) (b) (c) (d) (e) Automatic brake

Fig. 22 Scalamobile – principle of operation (a)-(d), automatic brake (e)

Illustration (a-d) courtesy of Max-Ability Inc.



(a) C-max stair-climber (b) stair edge brakes (c) climber operation

Fig. 23 C-max articulated lifting mechanism based stair-climbing wheelchair

Photos courtesy of Alber

- **Comments**

The addition of stair-climbing functionality by necessity increases a wheelchair's weight, however by making this functionality modular and easily removable from the wheelchair it can be attached only when required (Scalamobile) Fig. 21 [26]. Two pairs of wheels operate on separate axes, the orbiting motion is shown in Fig. 22(a)-(d). The C-max wheelchair operates in a similar manner to the Scalamobile except one pair of wheels is replaced with lifting protrusions as shown in Fig. 23(c). The respective stair edge auto brake mechanisms are pictured in Fig. 22(e) and Fig. 23(b).

The stair-climber described in Section 4 and pictured in Fig. 66(c) technically qualifies as a stair-climbing attachment. This stair-climber (KSC-C-10) has been developed by Kyowa Industries [27] in conjunction with Nagasaki University and associated research groups [28]. The operation is smooth and easy to operate. However the size and weight of the stair-climbing unit is much greater than such as the Scalamobile or C-max.

2.5 Wheel cluster based stair-climbers

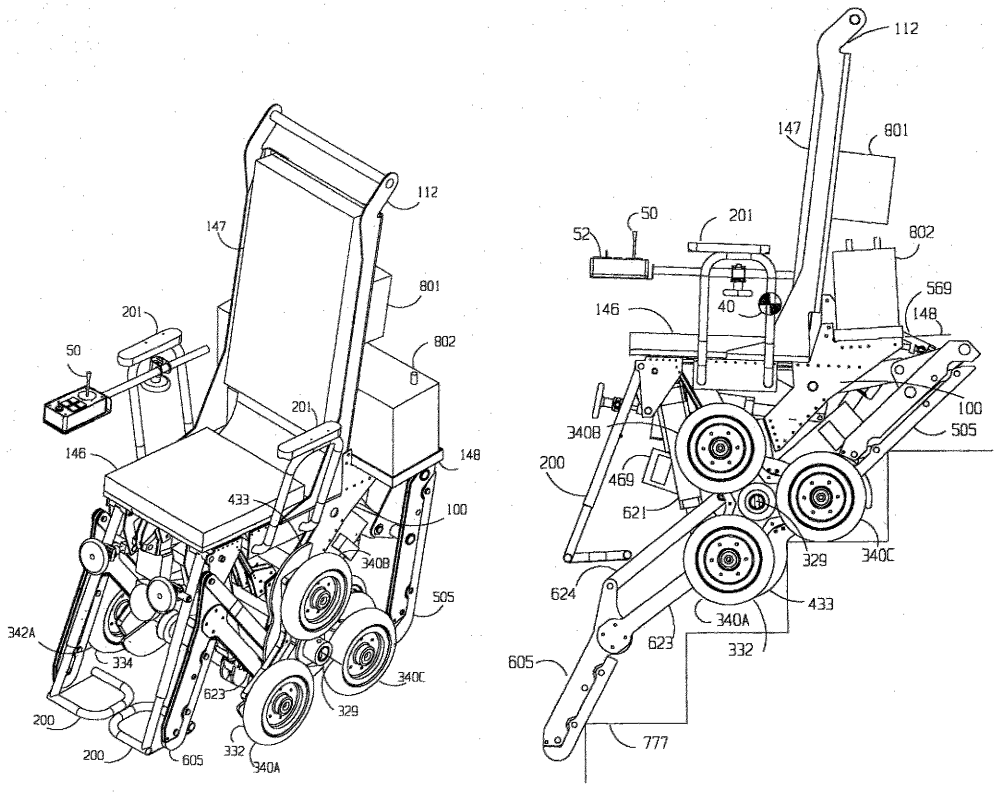
(a) three wheel cluster (b) four wheel cluster

Fig. 24 Powered single cluster stair-climbers

Photos courtesy of Hospimedica group and runsoft.com.cn

- **Features**
  - Stair-climbing ability
  - Suitable to almost all stairs
  - Compact
  - Operate as general purpose powered wheelchairs
  - Lightweight (cf. track based wheelchairs)

- **Negative points**
  - Requires assistance (one person) for stair operation
  - Orbital stair-climbing operation may be uncomfortable for passengers



(a) barrier free mode (b) stair-climb configuration

Fig. 25 Wheel cluster based stair-climber with articulated balancing sliders

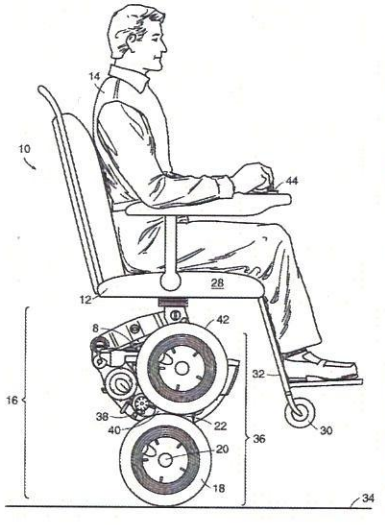
Illustrations courtesy of US Patent 6,484,829 B1

- **Comments**

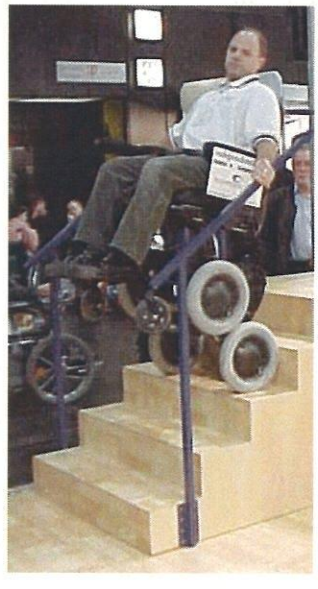
Wheel clusters in their simplest form adapt the most common means of transportation "the wheel" to the most common obstacle to the wheel "the stair". If a single wheel cluster is used, a balancing mechanism is required for any form of stair-climbing. The term "Single wheel cluster" in this paper refers to the lateral configuration of 2 identical clusters of wheels. Operation on stairs is similar to the Scalamobile as shown in Fig. 21(c), except the stair-climbing equipment is an integral part of the wheelchair, the models pictured in Fig. 24 also operate as standard powered wheelchairs, 3 wheel cluster Fig. 24(a) [25] and 4 wheel cluster Fig. 24(b) [29]. Fig. 24(b) differs in operation in that it uses four cluster wheels for barrier free operation, that is there are no auxiliary front wheels or casters. A variation to the single cluster stair-climber is detailed in [30], this mechanism is illustrated in Fig. 25 in barrier free and stair-climb modes respectively. The mechanism provides articulated front and rear sliders to maintain balance during stair negotiation therefore enabling autonomous stair-climbing operation.

2.6 COG modification wheel cluster based stair-climber

(a) barrier free mode



(b) standing mode



(c) hand rail assisted stair-climb

Fig. 26 COG modification stair-climber

Photos/ illustration courtesy of John Williamson (a) and (c), US patents 6,443,250 B1 (b)

- **Features**
  - Stair-climbing ability suitable to almost all stairs
  - Autonomous stair-climbing operation possible
  - Standing mode provided for eye level communication with standing persons and access to top shelves
  - Compact (cf. track based mechanism)
  - Operates as a general purpose powered wheelchair
  - Operates in almost all environments including sand, gravel, highly irregular surfaces and slopes up to ~25° (surface permitting) in the direction of desired travel
  - Lightweight (cf. track based wheelchairs)

- **Negative points**
  - Requires assistance (one person) or appropriate hand rail/s for stair operation
  - Must climb stairs backwards
  - Expensive ($29,000 US as at Nov 21 2002)
  - May be require prescription and special training (US FDA recommendation)
  - Orbital stair-climbing operation may be uncomfortable for passengers
  - Concern regarding balancing mechanism

- **Comments**

In the case of a wheelchair with CM (COG modification) an appropriately located hand-rail can be used by the operator (user) to provide commands for the balancing mechanism, alternatively operation by and assistant similarly to that shown in Fig. 21(c). Fig. 26(a) shows the iBOT™ 3000 wheelchair [31] [32] in barrier free mode, only the rear wheels make contact with the ground using the front casters to provide free wheeled steering. All four rear wheels are used to provide extra traction 4WD making operation on sand, gravel or unleveled surfaces possible. A standing mode illustrated in Fig. 26(b) is provided, by balancing on two wheels eye to eye contact with standing persons is possible as well as the reaching of upper shelves. Fig. 26(c) shows the stair-climbing operation, if a handrail is appropriately provided the user can negotiate the stairs unassisted. In the case of appropriate handrails not being available an assistant (person) is required. Autonomous operation on stairs using a single handrail is also possible.

2.7 Dual wheel cluster stair-climber

(a) barrier free mode (b) stair-climbing mode

Fig. 27 Dual cluster – front articulated stair-climber, "Freedom"

Photos courtesy of Tomo Co. Ltd and Tamagawa University

- **Features**
  - Stair-climbing ability suitable to most standard stairs
  - Autonomous stair-climbing operation possible
  - Operates as a general purpose powered wheelchair

- **Negative points**
  - Must climb stairs backwards
  - Orbital stair-climbing operation may be uncomfortable for passengers
  - Large (width 820mm cf. standard powered wheelchair)
  - Heavy (100Kg cf. standard powered wheelchair)

- **Comments**

A dual cluster – front articulated stair-climber, "Freedom" is shown in Fig. 27 [33]. This wheelchair operates as a standard powered wheelchair when configured as shown in Fig. 27(a),

using the rear wheels for drive and front freewheeling casters. The configuration is changed as shown in Fig. 27(b) for stair-negotiation. Stair-climbing is forward down and back up. The front cluster rotates passively during stair-negotiation.

2.8 Miscellaneous stair-assist and van entry mechanisms

(a) Overhead wheelchair hoist (b) Portable wheelchair lifter (c) Seat lift/ wheelchair

Fig. 28 Miscellaneous assistive mechanisms for stairs and van entry

Photos courtesy of Outa Co. Japan (a) Toyota (b) and (c)

- **Features**
  - Stair-climbing ability suitable to most standard stairs (overhead wheelchair hoist [34])
  - Van access for most wheelchairs and passenger possible (portable wheelchair lifter and seat lift/ wheelchair [35])
  - Van provided with built in dedicated seat/ wheelchair lifter (seat lift/ wheelchair)
  - Van seat operates as a general purpose operator assisted wheelchair (seat lift/ wheelchair)
  - Wheelchair lifter is lightweight and portable (portable wheelchair lifter)

- **Negative points**
  - Expensive and dedicated to a single set of stairs (overhead wheelchair hoist)
  - Lifting of standard manually propelled wheelchair not supported (seat lift/ wheelchair)
  - Powered wheelchairs not supported (portable wheelchair lifter)

- **Comments**

The provision of a seat which swivels out has become an option made available by most Japanese car manufactures, however the task of transfer to such as a wheelchair remains. One solution to this problem has been the provision of a seat which doubles as an assistant operated wheelchair shown in Fig. 28(c) [35].

2.9 Recent advances in mobility assistive devices for stairs or curbs, summary and discussion

Table 1 provides a broad categorization of curb or stair assist mobility enhancement devices available at the time of writing.

Stair-climbing wheelchairs rated as highest risk devices

Stair-climbing wheelchairs are currently rated as highest risk devices "Class III" alongside such as pacemakers (USA FDA.). Class III are defined generally as "life sustaining or life supporting, implanted in the body, or present an unreasonable risk of illness or injury." Furthermore the functionality they provide (stair-negotiation) is not considered necessary, rather such functionality is considered as "luxury." In light of such attitudes at government levels (UK, USA. etc.) the progress in regard to stair-climbing mobility has been/ is understandably slow.

Change to and from stair-angles

In regard to autonomous stair climbing vehicles the phases requiring greatest care are the entering or exiting of a stair climb at the top of a set of stairs. This usually requires the careful synchronizing of the mechanism's change of angle and change of angle of the chair base in a controlled manner. That is, to avoid a sudden and uncontrolled tilt from a level angle to the stair

angle (typically 35°) or visa versa.

Table 1 Broad categorization of curb or stair assist mobility assistance devices

Device	Advantages	Disadvantages
Curb assistive mechanism for wheelchairs Fig. 16.	Higher curbs possible, retrofitable, low cost, lightweight.	More turning space required, not compatible with all wheelchairs.
Curb capable powered wheelchairs and mobility scooters Fig. 17.	Excellent overall mobility in most environments including curb negotiation.	Additional weight makes assistance with stairs difficult, special provision required for entry to such as a van.
Track based stair climbers Fig. 19	Simple autonomous operation on stairs and/ or steep slopes possible. Operation as a standard wheelchair to some extent possible.	Only suits stairs with robust edges, typically not well suited to general purpose operation. Heavy, special provision required for entry to such as a van. Must negotiate stairs backwards.
Lightweight wheelchair stair-climbing attachments Fig. 21 and Fig. 23	Stair-climbing possible on most stairs with only one assistant, compact, lightweight.	Special training for assistant may be required. Orbital motion tends to passenger discomfort.
Wheel cluster based stair-climbers Fig. 24	Stair-climbing possible on most stairs with only one assistant, relatively compact. Operation similar to standard powered wheelchair possible.	Orbital motion may cause passenger discomfort. Special provision required for entry to such as a van.
COG modification wheel cluster based stair-climber Fig. 26	Excellent overall mobility in most environments including on sand, gravel and stairs with little or no assistance.	Concern regarding balancing mechanism. Special provision required for entry to such as a van. Must negotiate stairs backwards.
Dual wheel cluster stair-climber Fig. 27	Autonomous stair-climbing possible. Operation as a standard wheelchair to some extent possible.	Heavy, wide, special provision required for entry to such as a van. Must negotiate stairs backwards.
Misc. overhead wheelchair hoist Fig. 28(a)	Suitable to most stairs. Suitable to most wheelchairs.	Expensive, dedicated to a single set of stairs.
Misc. portable wheelchair lifter Fig. 28(b)	Van access for most lightweight wheelchairs and passenger. Portable, lightweight, low cost.	Powered wheelchairs not supported.
Misc. seat lift/ wheelchair Fig. 28(c)	Van access for dedicated seat/ wheelchair and passenger.	Transfer required if a manually propelled wheelchair is used.

This controlled tilt function is provided by the assistant in the case of single assistant mechanisms. However in the case of the single assistant mechanisms outlined in this section the maintenance of a constant seat angle is not possible. The seat angle is determined by the centred COG, that is, in the case of a single wheel cluster based mechanism the assistant must constantly alter the

wheelchair angle to counter the shifting COG. The provision of a mechanism to counter this COG shift, as well counter the orbital motion inherent would be desirable for both passenger comfort and safety. Some of the wheel cluster based mechanisms use solid rubber tyres, as noted in the previous section they tend to be less comfortable for the passenger and are prone to breaking (Scalamobile). The choice of solid rubber tires is assumed to reduce the size of the mechanism as well as increasing stability.

Scalamobile in Nagasaki

The Scalamobile (Section 2.4) has been used in Nagasaki for some years but noted to be quite uncomfortable for the person being carried and difficult to use. Special training is required for operators. Specific problems encountered on the slopes of Nagasaki were the automatic brake shown in Fig. 22(e) automatically locks the wheels when it drops over the front of a stair, however on roughly hewn or cast concrete stairs the brake often cuts in during use making operation very awkward. The inherent operator difficulty is partially being able to time the wheelchair to arrive at the edge of the stair for the next cycle illustrated in Fig. 22(a)-(d), and partially the inherent COG shift that occurs during the stepping cycle. The discomfort in being carried is the inherent oscillation that occurs on account of the orbital motion produced from the mechanism during stair climb. It must however be noted the orbital or stair-climbing speed is adjustable, therefore operating at a slower does reduce this. As with many such devices operator skill is central in providing user comfort.

COG modified wheel cluster based stair-climber

The iBOT™ 3000 perhaps represents the most advanced all purpose stair-climbing mechanism at the time of writing. US government approval gained Nov 21 2002, FDA advisors urged a few limitations namely to ensure patients can use the complex technology safely, a doctor's prescription and special training to operate it [36].

Regarding the choice of mobility assistive solutions

In regard to the overall issue of mobility assistive devices typically a range of options are available for any given disability, that is there is significant overlap. The choice of "best fit" will be influenced to some degree by the perceived social acceptability in any given culture at any given time. Further preference may be influenced by personal experience, for example negative

experiences or impressions of people who used this or that mobility assistance device [37]. It is largely the role of the "occupational therapist" (OT) to discern which device and or approach is best suited to any given individual. The decision must also by necessity reflect the longer term direction in which the disability is moving, whether the condition is expected to improve, be stable or degenerative.

Summary

This section outlined recent advances in mobility assistive devices for stairs assist and high step mechanisms available at the time of writing. A number of functions are not provided by any mechanisms to date. The highest curb or single step negotiable is 150mm, however entrance to a van or to a traditional Japanese home represent high single steps ranging up to about 75cm in height. Further all stairs climbing mechanisms ascend stairs in reverse. Clearly operating a vehicle in the direction of desired travel represents a more logical mode of operation. A solution to these and other problems is proposed in the following section "Proposed high step and stair-climbing mechanism."