Advanced Robotics, Vol. 14, No. 7, pp. 551–564 (2000)

Review paper

Rehabilitation robotics: a review

NORIYUKI TEJIMA
Department of Robotics, Ritsumeikan University 1-1-1 Noji-Higashi, Kusatsu, Shiga, Japan

Received 23 May 2000; accepted 7 July 2000

Abstract—This article reviews various selected literature on rehabilitation robotics. The literature was obtained mainly from journals and conference proceedings of the robotic, rehabilitative or biomedical engineering associations. It has been classified into three categories: rehabilitation robot systems, evaluation and key technologies. Commercially available robots, new projects, users' experiences and requirements, and fundamental research are introduced. A comprehensive list of references is provided.

Keywords: Assistive device; disabilities; health care; literature survey.

1. INTRODUCTION

Rehabilitation robotics is often only thought of as robotic aids to assist people handicapped by a manipulative disability [1]. However, recent research in rehabilitation robotics reveals more extended possibilities for the use of robot technology in rehabilitation [2]. Hillman defined rehabilitation robotics as the application of robotic technology to the rehabilitation needs of people with disabilities as well as the growing elderly population [3]. This extended definition includes augmentative mobility, robots for therapeutic training and robots for help care-givers. In this paper, the extended definition is adopted.

A large number of industrial robots are used to manufacture products worldwide. On the contrary, only hundreds of rehabilitation robots are practically used by people with disabilities [4]. This indicates that successful rehabilitation robots cannot be realized with application of only industrial robotic technologies. Rehabilitation robotics has many technical and non-technical problems. First, cost and maintenance are the most serious problems for popularization. Second, rehabilitation robots are used close to users and because of this proximity accidents can happen. To avoid injury to the end user, recent rehabilitation robots are designed to operate with extremely low power. This means that they can only work with light goods and can only move very slowly. Consequently, the tasks they can perform are very limited. Third, most users have physical or mental handicaps, making it difficult for them to operate a robot. An effective human interface is one of the key technologies for rehabilitation robotics. At present, the only way to adapt an interface to each user's various needs is through trial and error. Systematic adaptation should be developed in the future.

This paper presents a review of the recent literature devoted to the above problems in the area of rehabilitation robots. The review is divided into three inter-related sections: (1) rehabilitation robot systems, (2) evaluation and user requirements, and (3) key technologies for the future. In particular, the first section describes augmentative manipulation systems, augmentative mobilities, robots for therapeutic training and robots to assist help care-givers. The second section presents adaptation to individual users and the evaluation of different devices. The third section deals with basic research concerning human interfaces and safety.

2. REHABILITATION ROBOT SYSTEMS

2.1. Augmentative manipulation

2.1.1. Wheelchair robots. One of the major aims of rehabilitation robots is to pick and place objects. If the robots can be mounted on wheelchairs, this will be convenient for the wheelchair users. The most famous robot arm mounted on a wheelchair is the Manus [5–7], which has more than 100 users worldwide [8]. The Manus is also used as a base system in many research projects [9–15]. Many other robots have also been developed, such as the Helping Hand [16], a wheelchair-mounted robot from the Bath Institute of Medical Engineering [17, 18], the PLAYBOT for children [19], the KARES [20, 21], the QA manipulation Arm [22], the IMMEDIATE [23, 24], the Chamaeleon [25], a manipulator from Tokyo Denki University [26] and a project from the Bulgarian Academy of Science [27].

A manipulator mounted on a wheelchair should have at least 6 d.o.f. for multipurpose functionality. Operating those degrees of freedom is sometimes complex and troublesome for users. Some robots were designed to be operated by task-oriented commands, such as 'pick up the box' or 'pour the milk'. Those robots still have difficulties performing these tasks. Practical robots such as the Manus now rely upon users for detailed operations.

2.1.2. Workstations. The robotic workstation is mounted in a fixed position such as on a desk. As it performs specific tasks such as food preparation, feeding, handling floppy disks and books, and telephoning, users can operate it easier than a wheelchair robot. Because the objects which are handled by the robot should be set precisely, it is difficult in practice to adapt to the requirements of each user. The DeVAR [28, 29], the ProVAR [30, 31], the RAID [32, 33], the MASTER and the AFMASTER [34, 35] are included in this category.

2.1.3. Powered feeders. In general, a robot for a single task can be used more easily and be cheaper than a multipurpose robot. The Handy 1 [36, 37] is the bestselling rehabilitation robot in the world [38]. It allows disabled people, who would have to be fed by someone else, to eat a normal meal at their own pace. It also has optional functions for brushing teeth, shaving and applying make up. Easy operation allows even children and people with cognitive disabilities to use it. The ISAC [39, 40] and My Spoon [41] were also developed as feeding robots.

2.1.4. Mobile robots. The Care-O-bot [42], the WALKY [43, 44], the RETIMO [45], the ROMAN [46], the MOVAID [24, 47], URMAD [24, 48], a trolley-mounted robot from the Bath Institute of Medical Engineering [49], a mobile robotic platform form the University of Bremen [50], a health care robot from the California Institute of Technology [51] and a mobile robot developed by Shibaura Institute of Technology [52] are typical examples of mobile robots with a manipulator. They move to perform various tasks semi-autonomously. They are not practical yet because they need an extremely high level of intelligence.

2.1.5. Robotic orthoses. Powered upper-limb orthoses are a kind of rehabilitation robot mounted on a user's upper limb. MULOS [53, 54], a project of the AI DuPont Hospital for Children and Drexel University [55, 56], a power-assisted robotic orthosis developed by Ritsumeikan University [57, 58], a wire-driven orthosis from MITI [59] and a wire-driven orthosis developed by Kanagawa Institute of Technology [60] are examples of orthoses developed to date. Tremor suppression is a typical application for robotic orthoses [61, 62]. Most of the robotic orthoses were proposed to work also as therapeutic training machines. Because the orthosis should not apply excessive force and should be precisely adjusted to the user's upper limb, it is more difficult to develop than other types of rehabilitation robots.

2.1.6. Robotic rooms. A robotic room is a new concept proposed by Sato [63] where a functional living room assists the disabled or the elderly. The robotic room consists of multiple surrounding sensors to communicate with users by means of behavior media as well as multiple actuators to accommodate users. Casals proposed a robotized kitchen CAPDI which could contain different kinds of adapted elements [64]. They are not practical yet because of their high cost and the difficulties of adaptation.

2.2. Augmentative mobility

2.2.1. Robotic wheelchairs. Two kinds of robotic wheelchairs have been developed: one is a high-performance wheelchair, such as a wheelchair which can traverse steps, and the other is a semi-autonomous wheelchair which can be operated easily. In the first category, a gyro-balanced wheelchair was unveiled which could rear up on two wheels, climb stairs and traverse uneven terrain [65]. As far as I know, no technical report has been published; however, it was reported by the NBC news in 1999 that such a device would be commercialized by Johnson & Johnson within 24 months. Lawn [66] and Miyagi [67] also proposed wheelchairs for climbing stairs. Omnidirectional wheelchairs, such as the OMNI [68], the wheelchair developed by Fern University Hagan [69, 70], and a hybrid wheelchair/bed system [71] are other examples of high-performance wheelchairs.

There were various reports about a semi-autonomous wheelchair which detected obstacles and assisted users in steering: the VAHM wheelchair [72, 73], the Wheelesley [74, 75], the Senario [76, 77], the NavChair [78, 79], the MAid [80, 81], the Luoson [82], the TAO [83], the Bremen Autonomous Wheelchair [84], the VAHM project [85], a wheelchair designed by the University of Alcalá [86], a wheelchair from the Polytechnic University of Madrid [87], a wheelchair developed by Northeastern University [88], a wheelchair developed by the University of Texas at Austin [89], Bühlmeier's wheelchair robot [90], Trahanias's robotic wheelchair [91], a wheelchair from the University of Ancona [92], a wheelchair from Osaka University [93] and a wheelchair of the University from Portsmouth [94, 95]. However, the aim of most of the projects was research on control methods. Only a few of these wheelchairs were practical.

2.2.2. Mobility aids for visually impaired people. Because of a lack of recognition of environmental information, visually impaired people have difficulties in independent walking. In order to overcome these difficulties, rehabilitation robots have been developed, which detected obstacles and provided navigational assistance. The PAM-AID [96–98], the Navbelt [99], the HITOMI [100, 101], the GuideCane [102] and the Robotic Cane [103] were typical systems. PAM-AID and HITOMI are mobile robots like walkers. The Navbelt is a wearable system, while the GuideCane and the Robotic Cane are used like a cane.

2.2.3. Walking support systems for the elderly. Walking is an essential activity for daily living. Rehabilitation robots which assist elderly people in standing up and in sitting down, support their weight in walking, and avoid their falls were proposed. Hitachi Ltd developed a walker-type power-assisted walking support system which moved smoothly by application of a weak force [104]. Suzuki developed a hoist-type system, which was used indoors [105].

2.3. Therapy robots

Rehabilitation robots have been applied to physical and occupational therapy. Most of the research was for upper-limb exercises. Some tried to perform existing training methods by robots for taking a load off of the therapist, others aimed at new therapies which can be performed only by robots. A project of the University of California, Berkeley [106], the MIT-Manus [107–109], the ARM Guide [110], a project of VA Palo Alto HCS [111, 112], a research effort at Leeds University [113, 114], a project from the University of Delaware [115], a project from Loughborough University [116], and a system from Harvard University and Boston Biomotion Inc. [117] were typical projects. For lower-limb exercises, the REHABOT for gait training [118] and the TEM [119, 120] were proposed.

2.4. Robots for help care-givers

Rehabilitation robots operated by nurses or care-givers, such as robotic devices that move a patient's entire body, were designed not for independent living of the disabled and the elderly, but for lightening the heavy burden of care-givers. This type of robot was mainly proposed in Asian countries [121–123]. As robots have to apply forces to the disabled or the elderly in many caring tasks, safety is the most important factor.

Robots for meal delivery, floor cleaning or bed making can be included in this category [124, 125]. Such robots do not interact with patients; however, they contribute to improve the quality of patients' lives by supporting care-givers.

3. ADAPTATION, EVALUATION AND USER REQUIREMENTS

Rehabilitation robots should be evaluated by users. At an early stage, rehabilitation robots were evaluated by only a few users for a short period. However, some rehabilitation robots have now been commercialized and hundreds of people with disabilities use them practically. They have proven the effectiveness of these rehabilitation robots in improving the quality of their lives. They have shown unexpected ways of use, their veiled requirements and problems of the systems. The reports about experimental and practical usage of rehabilitation robots are treasure boxes to find hints for developing better systems.

Many papers evaluating of the Manus have been published. Gelderblom interviewed 13 users of the Manus and tried to make a user profile [126]. The results were informative. The Manus is often used to eat or drink, but very seldom for the preparation of food or drinks. It is hardly used during washing. It is often used during the use of a handkerchief, brushing of teeth and using an electric razor, and for scratching. It is not used while dressing or undressing, but it is used in adjusting clothing or glasses. Only two of the users surveyed used the Manus when using the toilet. Half of the users used the Manus for taking mediation. It is used for applying a stamp with the users' signature, using a public phone and as an aid for reading. The report also showed problems associated with the Manus: its small power, small workspace, slow speed, less precise control, the expanded width of the combination of wheelchair and Manus, etc.

Rose analyzed 27 Manus users [127]. Of these users, 78% could use the Manus after 2 days of learning. Contrary to Gelderblom's result, 81% of the users said that the velocity was good; 70% thought that the noise level was low, 52% used the Manus system without problems of maneuverability, 70% thought that the Manus could be useful at home and 63% for leisure. With regard to the arm, the Cartesian mode was most often used by users, the joint mode and cylindrical mode could be used, and the drinking mode was nice. The interface and maintenance were also discussed.

Eftring evaluated the Manus in a trial where eight people with disabilities used it for 1 or 2 days [128]. The results were that only one user wanted to have the

Manus, and the others thought it was too large, too heavy and too difficult to control. However, four users would like the Manus if it the following points were improved: the interface, the method of mounting to a wheelchair, the size, the weight and the payload. Half of the users thought it was too slow. Most of the difficulties encountered when using the Manus were caused by the interface. Bühler [129] and Zeelenberg, who was the father of a Manus user [130], also pointed out that most of the problems with the Manus were related to the input device.

Topping, who had developed the Handy 1, evaluated it and its new applications [131–133]. Three disabled people used Handy 1 for hygienic tasks, i.e. washing, shaving and teeth cleaning, and they enjoyed the experience of being able to wash, to clean their teeth and to shave themselves, and thought that the Handy 1 systems would be greatly beneficial to them. Three children with cerebral palsy tried to use the Handy 1 to draw and found problems due to some limitations in the current design of the system. The Handy 1 was not suitable for some users; one found great difficulty in seeing the control LEDs because of his reclining position and the present Handy 1 activities were not challenging enough for another, which might lead to boredom and frustration.

O'Connell, who has cerebral palsy, reported her experiences using the Handy 1 for 3 years [134]. The Handy 1 was the best machine for her to feed herself, mainly because the amount of movement required to operate it was minimal. Also, she found that the Handy 1 provided a sort of physiotherapy for her. Her posture improved, and her movements felt more controlled and less jerky than when she had first begun using the system. She thought that the £4000 she spent was not a waste of money.

Pinnington and Hegarty evaluated the Handy 1 system [135, 136]. In their study, 20 children with severe neurological impairments had used the Handy 1 for eating by themselves for more than 9 months. All of the children, except two, could use the robot. In one case, difficulties arose because the child had insufficient head control in the midrange of neck flexion, while the other had insufficient control of trunk flexion in sitting. Three children needed encouragement to attend and frequent prompting was necessary to press the switch. Reliability of the device was also reported; technical faults occurred (a defective plug, an incorrectly aligned cog and wire pulleys), and numerous problems were experienced with the durability of the commercially bought stalk wobble switches and goosenecks which were used as input devices. Their results showed that the robot demanded the active participation of the user in the food-delivery process, and no change occurred in the amounts of energy and protein consumed. The negative factors of increased meal duration and reduced eating efficiency outweighed the advantages for their children.

Other rehabilitation robots for augmentative manipulation, such as the Helping Hand [137], the Master [138, 139], the RAID [140], the DeVAR [141], the Inventaid [142], the trolley mounted robot from the Bath Institute of Medical Engineering [143], the Middlesex Rehabilitation Robotic Arm [144], the OSU/ASEL workstation [145] and the Neil Squire Foundation robotic-assistive appliance [146], have also been evaluated. A trial adaptation of a commercially available robotic arm for children with physical disabilities to interact in a play and exploration activity was also reported [147].

Rehabilitation robots have sometimes been evaluated by questionnaires or interviews as before. Subjective evaluation is important to reveal the users' requirements, while quantitative analysis is useful to know the effectiveness or the performance of the robots. From this point of view, some kinds of standardized tests or evaluation procedures have been proposed [148–151]. With regard to the human interface, quantitative evaluation methods of upper-arm mobility have also been proposed [152, 153].

There is a small amount of literature concerning evaluation for augmentative mobility, which was mainly written by the developers. A report that two persons with multiple disabilities used a mobile robot [154], the automatic adaptation in the NavChair wheelchair [155] and the evaluation of the PAM-AID for frail and elderly visually impaired persons [156] were published.

The economics of rehabilitation robots were also analyzed [4, 157, 158]. There are many potential users, although the market is predicted to grow slowly. For explosive growth in the market, major technical and cost breakthroughs are necessary.

4. KEY TECHNOLOGIES

4.1. Safety

Robots are essentially dangerous and, with their use, absolute safety does not exist. These two facts lead to difficulties of avoiding accidents involving rehabilitation robots. However, basic technology for minimizing the risks should be clarified. Today, safety should be the prime concern in the design of robots. Ikuta proposed a new general method to make a quantitative evaluation of the effectiveness of each safety strategy [159]. Yamada proposed a human-safety-oriented robot design based on human pain tolerance [160]. Tejima proposed a new mechanical apparatus for force limitation [161]. Wakita asserted that information sharing between a user and a robot would be important for safety [162]. This research is not practical yet because of the underlying assumptions. Further discussion of this field will be necessary.

4.2. Interfaces

Industrial robots are operated by specialists, while rehabilitation robots are used by non-specialists with disabilities. A good user-friendly interface is highly desirable for the acceptance of rehabilitation robots, especially for multipurpose robots. However, results showed that many of the problems with rehabilitation robots were still centered in the human interface. Usability should be improved by basic research and development.

Various studies on the human interface were proposed. As voice is the most natural form of communication, speech commands for operation were sometimes proposed [14, 163–165]. Gestures [164, 165], head movements [166–168], shoulder movements [169], eye movements [13], electromyography [170] and motor cortex activities [171] were all tested as control signals. As interface devices, a multiple degrees of freedom joystick [172, 173] and a personal computer-based interface, such as a graphical user interface for task planning, simulation and execution [174, 175], and an iconic interface [176] were used. Rapid prototyping is a promising method for adapting rehabilitation robots to user requirements [177–184]. The M3S communication standard for integrated user interfaces [185–187] and a generalized interface that allows a personal computer to control robotic devices [188] are also important developments. A Model Human Processor for disabled users [189] was intended to help designers build an image of a system. Modeling human dynamics is necessary for robotic orthoses and robotic therapy [190–192]. These basic studies will lead to the realization of useful rehabilitation robots.

5. CONCLUSIONS

Trends in rehabilitation robots were reviewed. Key research and development issues were described. Hundreds of rehabilitation robots have been sold in the last 10 years. However, it was a negligible quantity compared with the quantity of users and the quantity of industrial robots. This means that many research, development and economical issues in rehabilitation robotics remain to be solved. The collaboration of researchers and a wealth of practical experiences are necessary to popularize rehabilitation robots.

REFERENCES

1. M. Kassler, *Robotica* **11**, 495–516 (1993).
2. H. Th. P. Knops, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 30–33 (1999).
3. M. Hillman, *Robotica* **16**, 485 (1998).
4. R. M. Mahoney, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 12–17 (1997).
5. H. H. Kwee, *IEEE Eng. Med. Biol.* **14**, 330–335 (1995).
6. H. H. Kwee, *Robotica* **16**, 491–498 (1998).
7. H. Kwee, J. Quaedackers, E. van de Bool, L. Theeuwen and L. Speth, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 106–114 (1999).
8. J. A. van Woerden and K. M. van de Hel, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 79–86 (1999).
9. N. Didi, M. Mokhtari and A. Roby-Brami, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 329–333. IOS Press, Amsterdam (1999).
10. N. Didi, M. Mokhtari and A. Roby-Brami, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 92–98 (1999).
11. B. Higgins, R. W. Glass, L. Leiber and R. Foulds, in: *Proc. RESNA 97*, pp. 384–386 (1997).
12. A. Wisaksana, G. Verberg and S. Naumann, in: *Proc. RESNA 95*, pp. 478–480 (1995).

13. A. Cheetham, M. Milner and G. Verburg, in: *Proc. RESNA 94*, pp. 454–456 (1994).
14. H. Heck, M. Larsson, C. Bühler and G. Bolmsjö, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 297–301. IOS Press, Amsterdam (1999).
15. C. Truche, M. Mokhtari and C. Vallet, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 302–307. IOS Press, Amsterdam (1999).
16. S. J. Sheredos, B. Taylor, C. B. Cobb and E. E. Dann, in: *Proc. RESNA 95*, pp. 493–495 (1995).
17. M. Hillman, K. Hagan, S. Hagan, J. Jepson and R. Orpwood, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 86–91 (1999).
18. M. R. Hillman, K. Hagan, S. A. Hagan, J. Jepson, R. D. Orpwood and T. D. Adlam, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 316–321. IOS Press, Amsterdam (1999).
19. J. K. Tsotsos, G. Verghese, S. Dickinson, M. Jenkin, A. Jepson, E. Milios, F. Nuflo, S. Stevenson, M. Black, D. Metaxas, S. Culhane, Y. Ye and R. Mann, *Image Vision Comput.* **16**, 275–292 (1998).
20. W.-K. Song, H.-Y. Lee, J.-S. Kim, Y.-S. Yoon and Z. Bien, in: *Proc. Int. Conf. IEEE/EMBS*, pp. 2682–2685 (1998).
21. J.-W. Jung, W.-K. Song, H. Lee, J.-S. Kim, Z. Bien, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 42–49 (1999).
22. R. G. Burrows and R. E. Hannah, in: *Proc. RESNA 95*, pp. 505–507 (1995).
23. T. Øderud, G. Boersma and J. A. van Woerden, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 65–66 (1994).
24. P. Dario, E. V. Genovese and M. Toro, *Robotics Autonomous Syst.* **18**, 225–234 (1996).
25. K. McClenathan and T. Rahman, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 67–73 (1999).
26. Y. Saito, H. Yonemoto, H. Azuma and T. Inoue, in: *Proc. ECART3*, pp. 182–184 (1995).
27. D. Stefanov, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 207–215 (1999).
28. B. Taylor, M. E. Cupo and S. J. Sheredos, *Am. J. Occupational Ther.* **47**, 1009–1013 (1993).
29. H. F. Machiel Van der Loos, *IEEE Trans. Rehabil. Eng.* **3**, 46–55 (1995).
30. H. F. M. Van der Loos, J. J. Wagner, N. Smaby, K. Chang, O. Madrigal, L. J. Leifer and O. Khatib, in: *Proc. RESNA 99*, pp. 134–136 (1999).
31. H. F. M. Van der Loos, J. J. Wagner, N. Smaby, K. Chang, O. Madrigal, L. J. Leifer and O. Khatib, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 741–746 (1999).
32. H. Eftring, *Lecture Notes Comp. Sci.* **860**, 120–128 (1994).
33. T. Jones, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 201–206 (1999).
34. R. Gelin, F. Coulon-Lauture, B. Lesigne, J.-M. Le Blanc and M. Busnel, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 149–155 (1999).
35. R. Cammoun, J.-M. Detriché, F. Lauture and B. Lesigne, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 27–29 (1994).
36. M. Topping and J. Smith, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 244–249 (1999).
37. M. Topping and J. Smith, *The Industrial Robot* **25**, 316–320 (1998).
38. R. M. Mahoney, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 12–17 (1997).
39. A. Kara, K. Kawamura, S. Bagchi and M. El-Gamal, *IEEE Control Syst. Mag.* **12**, 71–76 (1992).
40. K. Kawamura, S. Bagchi, M. Iskarous and M. Bishay, *IEEE Trans. Rehabil. Eng.* **3**, 14–21 (1995).
41. S. Ishii, S. Tanaka and F. Hiramatsu, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1308–1313 (1995).
42. C. Schaeffer and T. May, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 340–345. IOS Press, Amsterdam (1999).
43. H. Neveryd and G. Bolmsjö, in: *The European Context for Assistive Technology (Proc. 2nd. TIDE Congr.)*, pp. 366–370. IOS Press, Amsterdam (1995).

44. H. Neverya and G. Bolmsjö, *Lecture Notes Comp. Sci.* **860**, 129–135 (1994).
45. B. J. F. Driessen, J. A. v. Woerden, G. Bolmsjö and O. Buckmann, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 129–135 (1999).
46. E. Ettelt, R. Furtwängler, U. D. Hanebeck and G. Schmidt, *J. Intell. Robotic Syst.* **22**, 191–209 (1998).
47. P. Dario, E. Gulielmelli, C. Laschi and G. Teti, *Technol. Disability* **10**, 77–93 (1996).
48. P. Dario, E. Guglielmelli and C. Mulè, in: *Proc. RESNA 95*, pp. 514–516 (1995).
49. M. Hillman, in: *Proc. RESNA 96*, pp. 357–359 (1996).
50. O. Buckmann, M. Krömker and U. Berger, *J. Intell. Robotic Syst.* **22**, 331–350 (1998).
51. P. Fiorini, K. Ali and H. Saraji, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1271–1276 (1996).
52. T. Komeda, H. Matsuoka, Y. Ogawa, P. B. Zobel, T. Uchida, H. Koyama, M. Miyagi and H. Funakubo, in: *Proc. ECART3*, pp. 179–181 (1995).
53. G. R. Johnson and M. A. Buckley, in: *Proc. RESNA 97*, pp. 399–401 (1997).
54. A. Yardley and D. A. Carus, in: *Proc. RESNA 97*, pp. 402–404 (1997).
55. T. Rahman, S. Stroud, R. Ramanathan, M. Alexander, R. Seliktar and W. Harwin, *Technol. Disability* **5**, 197–203 (1996).
56. W. Sample, R. Ramanathan, T. Rahman, S. Eberhardt, R. Seliktar and M. Alexander, in: *Proc. RESNA 99*, pp. 137–139 (1999).
57. K. Nagai, I. Nakanishi and T. Kishida, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 270–275 (1999).
58. K. Nagai, I. Nakanishi, H. Hanafusa, S. Kawamura, M. Makikawa and N. Tejima, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 3486–3491 (1998).
59. K. Homma and T. Arai, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1302–1307 (1995).
60. Y. Takahashi and T. Kobayashi, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 216–226 (1999).
61. C. A. Avizzano and M. Bergamasco, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 261–269 (1999).
62. S. Pledgie, K. Barner and S. Agrawal, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 16–26 (1999).
63. T. Sato, Y. Nishida and H. Mizoguchi, *Robotics Autonomous Syst.* **18**, 185–194 (1996).
64. A. Casals, R. Merchan, E. Portell, X. Cufí and J. Contijoch, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 346–351. IOS Press, Amsterdam (1999).
65. *Sci. Am.* (Sept), 28–29 (1999).
66. M. Lawn and T. Takeda, in: *Proc. Int. Conf. IEEE/EMBS*, pp. 2678–2681 (1998).
67. M. Miyagi, T. Uchida, T. Komeda, H. Koyama and H. Funakubo, *J. Jpn Soc. Precision Engng* **64**, 403–407 (1998).
68. U. Borgolte, H. Hoyer, C. Bühler, H. Heck and R. Hoelper, *J. Intell. Robotic Syst.* **22**, 233–253 (1998).
69. H. Hoyer and R. Hoelper, in: *Rehabilitation Technology Strategy for the European Union (Proc. 1st. TIDE Congr.)*, pp. 93–97. IOS Press, Amsterdam (1993).
70. H. Hoyer, U. Borgolte and R. Hoelper, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 31–34 (1997).
71. S. Mascaro and H. H. Asada, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 399–405 (1998).
72. G. Bourhis and Y. Agostini, *J. Intell. Robotic Syst.* **22**, 269–287 (1998).
73. G. Bourhis and P. Pino, *IEEE Trans. Rehabil. Eng.* **4**, 7–12 (1996).
74. H. A. Yanco, *Lecture Notes Comp. Sci.* **1458**, 256–268 (1998).
75. H A. Yanco and J. Gips, in: *Proc. RESNA 98*, pp. 298–300 (1998).
76. P. D. Beattie and J. M. Bishop, *J. Intell. Robotic Syst.* **22**, 255–267 (1998).

77. K. I. Katevas, S. G. Tzafestas and C. G. Pnevmatikatos, *J. Intell. Robotic Syst.* **22**, 289–314 (1998).
78. S. P. Levine, D. A. Bell, L. A. Laros, R. C. Simpson, Y. Koren and J. Borenstein, *IEEE Trans. Rehabil. Eng.* **7**, 443–451 (1999).
79. R. C. Simpson, S. P. Levine, D. A. Bell, L. A. Jaros, Y. Koren and J. Borenstein, *Lecture Notes Comp. Sci.* **1458**, 235–255 (1998).
80. E. Prassler, J. Scholz and P. Fiorini, *Int. J. Robotics Res.* **18**, 711–727 (1999).
81. E. Prassler, J. Scholz, M. Strobel and P. Fiorini, *Lecture Notes Comp. Sci.* **1724**, 68–95 (1999).
82. R. C. Luo, T. M. Chen, C.-Y. Hu and Z. Hung Hsiao, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 2014–2019 (1999).
83. T. Gomi and A. Griffith, *Lecture Notes Comp. Sci.* **1458**, 150–178 (1998).
84. B. Krieg-Brückner, T. Röfer, H.-O. Carmesin and R. Müller, *Lecture Notes Comp. Sci.* **1404**, 373–397 (1998).
85. P. Pino, Y. Agostini, G. Bourhis, J. M. André, B. Brugerolle and H. De Barmon, in: *Proc. RESNA 95*, pp. 508–510 (1995).
86. P. Martín, M. Mazo, I. Fernández, J. L. Lázaro, F. J. Rodríguez and A. Gardel, *Microprocess. Microsyst.* **23**, 1–6 (1999).
87. F. Matía, R. Sanz and E. A. Puente, *J. Intell. Robotic Syst.* **22**, 211–232 (1998).
88. J. D. Crisman and M. E. Cleary, *Lecture Notes Comp. Sci.* **1458**, 137–149 (1998).
89. W. S. Gribble, R. L. Browning, M. Hewett, E. Remolina and B. J. Kuipers, *Lecture Notes Comp. Sci.* **1458**, 179–193 (1998).
90. A. Bühlmeier, P. Steiner, M. Rossmann, K. Goser and G. Manteuffel, *Lecture Notes Comp. Sci.* **1327**, 727–732 (1997).
91. P. E. Trahanias, M. I. A. Lourakis, A. A. Argyros and S. C. Orphanoudakis, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1265–1270 (1997).
92. S. Fioretti, T. Leo and S. Longhi, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 393–398 (1998).
93. Y. Kuno, S. Nakanishi, T. Murashima, N. Shimada and Y. Shirai, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 2590–2595 (1999).
94. M. J. Goodwin, D. A. Sanders and I. J. Stott, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 131–134 (1997).
95. D. Sanders and I. Stott, *The Industrial Robot* **26**, 466–475 (1999).
96. G. Lacey and K. M. Dawson-Howe, *Robotics Autonomous Syst.* **23**, 245–252 (1998).
97. G. Lacey, S. MacNamara, H. Petrie, H. Hunter, M. Karlsson, N. Katevas and J. Rundenshöld, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 60–66 (1999).
98. S. MacNamara and G. Lacey, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 163–169 (1999).
99. S. Shoval, J. Borenstein and Y. Koren, *IEEE Trans. Biomed. Eng.* **45**, 1376–1386 (1998).
100. S. Kotani, H. Mori and N. Moghaddam Charkari, *Robotics Autonomous Syst.* **18**, 235–242 (1996).
101. S. Kotani, H. Mori and N. Kiyohiro, *Robotics Autonomous Syst.* **17**, 119–128 (1996).
102. J. Borenstein and I. Ulrich, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 1283–1288 (1997).
103. P. Aigner and B. McCarragher, *IEEE Control Syst. Mag.* **19**, 40–46 (1999).
104. Y. Nemoto, S. Egawa, A. Koseki, S. Hattori, T. Ishii and M. Fujie, in: *Proc. Int. Conf. IEEE/EMBS*, pp. 2693–2695 (1998).
105. M. Suzuki, K. Masamune, L.-J. Ji, T. Dohi and H. Yano, *Robotica* **16**, 537–542 (1998).
106. P. S. Lum, D. J. Reinkensmeyer and S. L. Lehman, *IEEE Trans. Rehab. Eng.* **1**, 185–191 (1993).
107. H. I. Krebs, N. Hogan, W. Hening, S. Adamovich and H. Poizner, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 27–33 (1999).

108. H. I. Krebs, N. Hogan, B. T. Volpe, M. L. Aisen, L. Edelstein and C. Diels, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 34–41 (1999).
109. M. Lipson Aisen, H. Igo Krebs, N. Hogan, F. McDowell and B. T. Volpe, *Arch. Neurol.* **54**, 443–446 (1997).
110. D. J. Reinkensmeyer, B. D. Schmit and W. Z. Rymer, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 9–15 (1999).
111. P. S. Lum, C. G. Burgar and H. F. M. Van der Loos, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 107–110 (1997).
112. P. S. Lum, M. Van der Loos, P. Shor and C. G. Burgar, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 235–239 (1999).
113. M. Austin, J. Cozens, A. Plummer and B. Seedhom, in: *Proc. RESNA 98*, pp. 292–294 (1998).
114. J. A. Cozens, *IEEE Trans. Rehabil. Eng.* **7**, 254–256 (1999).
115. R. Rao, S. K. Agrawal and J. P. Scholz, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 187–200 (1999).
116. A. J. Taylor, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 39–42 (1997).
117. Y. Matsuoka and L. C. Miller, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 177–182 (1999).
118. N. A. Siddiqi, T. Ide, M. Y. Chen and N. Akamatsu, *Am. J. Phys. Med. Rehabil.* **73**, 212–216 (1994).
119. T. Sakaki, *The Industrial Robot* **26**, 446–450 (1999).
120. T. Sakaki, S. Okada, Y. Okajima, N. Tanaka, A. Kimura, S. Uchida, M. Taki, Y. Tomita and T. Horiuchi, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 183–186 (1999).
121. Y. Hayakawa, T. Yamamoto, N. Iseki and Y. Amano, in: *Proc. Int. Conf. IEEE/EMBS*, pp. 2674–2677 (1998).
122. C. Huang, S. Xiao, J. Zhang and G. Xu, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 51–54 (1997).
123. A. M.-K. Wong, M.-Y. Lee and S. F.-T. Tang, *Chang Keng I Hsueh* **20**, 272–279 (1997).
124. J. F. Engelberger, *Robotica* **11**, 517–523 (1993).
125. K. Williams, *Nursing Standard* **10**, 13 (1996).
126. G. J. Gelderblom, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 8–14 (1999).
127. C. Rose, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 107–112 (1999).
128. H. Eftring and K. Boschian, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 136–141 (1999).
129. C. Bühler, *Int. J. Industrial Ergonomics* **17**, 187–192 (1996).
130. A. P. Zeelenberg, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 87–92 (1999).
131. M. Topping, *Robotica* **11**, 525–528 (1993).
132. H. Heck, J. Smith, C. Bühler and M. Topping, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 322–328. IOS Press, Amsterdam (1999).
133. J. Smith and M. Topping, *Br. J. Occupational Ther.* **59**, 565–569 (1996).
134. S. O'Connell and M. Topping, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 115–121 (1999).
135. L. L. Pinnington and J. R. Hegarty, *Clin. Rehabil.* **8**, 258–265 (1994).
136. L. Pinnington and J. Hegarty, *Dysphagia* **14**, 17–26 (1999).
137. S. J. Sheredos and B. Taylor, in: *Proc. RESNA 97*, pp. 378–380 (1997).
138. R. Cammoun, J.-M. Détriché, F. Lauture and B. Lesigne, *Robotica* **11**, 535–540 (1993).
139. J. S. Morvan, J. P. Guichard and V. Torossian, *Int. J. Rehabil. Res.* **20**, 193–197 (1997).
140. C. Danielsson and L. Holmberg, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 7–11 (1994).
141. D. S. Lees and L. J. Leifer, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 19–23 (1994).
142. J. Mattie and R. Hannah, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 13–5 (1994).
143. M. Hillman and J. Jepson, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 95–98 (1997).

144. B. N. Parsons, P. R. Warner, A. White and R. Gill, in: *Proc. RESNA 97*, pp. 411–413 (1997).
145. R. Howell, C. Stranger and B. Chipman, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 165–168 (1994).
146. G. E. Birch, *Robotica* **11**, 529–534 (1993).
147. A. Cook and K. Howery, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 291–296. IOS Press, Amsterdam (1999).
148. J. L. Schuyler, R. M. Mahoney and P. A. Hove, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 99–102 (1997).
149. J. L. Schuyler, R. M. Mahoney and P. A. Hove, in: *Proc. RESNA 97*, pp. 408–410 (1997).
150. J. L. Mattie and R. E. Hannah, in: *Proc. RESNA 95*, pp. 499–501 (1995).
151. J. M. Hammel, *IEEE Trans. Rehabil. Eng.* **3**, 56–61 (1995).
152. M. Mokhtari, N. Didi and A. Roby-Brami, in: *Proc. RESNA 98*, pp. 289–291 (1998).
153. M. Mokhtari, A. Roby-Brami and I. Laffont, in: *Proc. RESNA 97*, pp. 420–422 (1997).
154. G. E. Lancioni, D. Oliva and M. Signorino, *Percept. Mot. Skills* **79**, 843–848 (1994).
155. R. C. Simpson and S. P. Levine, *IEEE Trans. Rehabil. Eng.* **7**, 452–463 (1999).
156. A.-M. O'Neill, H. Petrie, B. Gallagher, H. Hunter, G. Lacey and N. Katevas, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 352–356. IOS Press, Amsterdam (1999).
157. L. P. de Witte, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 15–20 (1999).
158. H. J. A. Stuyt, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 61–66 (1999).
159. K. Ikuta and M. Nokata, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 2065–2072 (1999).
160. Y. Yamada, Y. Hirasawa, S. Huang, Y. Umetani and K. Suita, *IEEE/ASME Trans. Mechatron.* **2**, 230–236 (1997).
161. N. Tejima, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 74–78 (1999).
162. Y. Wakita, S. Hirai, T. Hori, R. Takada and M. Kakikura, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 3474–3479 (1998).
163. B. Borgerding, O. Ivlev, C. Martens, N. Ruchel and A. Gräser, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 286–290. IOS Press, Amsterdam (1999).
164. Z. Kazi and R. Foulds, *Robotica* **16**, 509–516 (1998).
165. Z. Kazi, S. Chen, M. Beitler, D. Chester and R. Foulds, *Lecture Notes Comp. Sci.* **1458**, 194–210 (1998).
166. S. Chen, T. Rahman, R. Foulds, E. Heredia and W. Harwin, *Robotica* **16**, 499–507 (1998).
167. S. Chen, T. Rahman and W. Harwin, *IEEE Trans. Rehabil. Eng.* **6**, 406–414 (1998).
168. P. Song, V. Kumar, R. Bajcsy, V. Krovi and R. Mahoney, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 122–128 (1999).
169. D. Fass, T. Rahman and R. Seliktar, in: *Proc. RESNA 95*, pp. 520–522 (1995).
170. O. Fukuda, T. Tsuji, A. Ohtsuka and M. Kaneko, in: *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 3492–3497 (1998).
171. M. Burrow, J. Dugger, D. R. Humphrey, D. J. Reed and L. R. Hochberg, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 83–86 (1997).
172. A. Wisaksana, G. Verberg and S. Naumann, in: *Proc. RESNA 95*, pp. 478–480 (1995).
173. S. Scattareggia Marchese, G. Parrini, M. A. Buckley, G. Neff, R. Platts and G. R. Johnson, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 143–146 (1997).
174. J. J. Wagner, H. F. M. Van der Loos, N. Smaby, K. Chang and C. Burgar, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 250–254 (1999).
175. J. J. Wagner, H. F. M. Van der Loos and L. J. Leifer, in: *Proc. RESNA 98*, pp. 286–288 (1998).
176. J. L. Dallaway, in: *Proc. RESNA 96*, pp. 339–341 (1996).
177. S. Keates, J. Clarkson and P. Robinson, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 156–162 (1999).
178. B. Dowland, J. Clarkson and R. Cipolla, *Robotica* **16**, 517–521 (1998).

179. K. L. McClenathan, M. T. Beitler and R. M. Mahoney, in: *Proc. RESNA 97*, pp. 381–383 (1997).
180. M. T. Beitler, W. S. Harwin and R. M. Mahoney, in: *Proc. RESNA 96*, pp. 360–362 (1996).
181. V. Krovi, V. Kumar, G. K. Anathasuresh and J.-M. Vezien, *Trans. ASME J. Mech. Des.* **121**, 456–458 (1999).
182. M. Fridenfalk, U. Lorentzon and G. Bolmsjö, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 308–315. IOS Press, Amsterdam (1999).
183. B. J. F. Driessen and J. A. V. Woerden, in: *Assistive Technology on the Threshold of the New Millennium*, pp. 334–339. IOS Press, Amsterdam (1999).
184. G. Cremers and H. Kwee, in: *Proc. Workshop Rehabilitation Robotics AAATE '99*, pp. 113–118 (1999).
185. A. Wisaksana, G. Verburg and S. Naumann, in: *Proc. RESNA 96*, pp. 336–338 (1996).
186. G. Verburg, M. Milner, A. Cheetham and A. Wisaksana, in: *Proc. ECART3*, pp. 174–176 (1995).
187. H. Kwee, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 91–94 (1997).
188. R. W. Glass, B. Higgins and R. Foulds, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 127–130 (1997).
189. S. Keates and P. Robinson, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 75–78 (1997).
190. W. Harwin and S. Wall, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 170–176 (1999).
191. W. S. Harwin, L. O. Leiber, G. P. G. Austwick and C. Dislis, *Robotica* **16**, 523–530 (1998).
192. M. S. Ben-Lamine, S. Shibata, K. Tanaka and A. Shimizu, in: *Proc. Int. Conf. on Rehabilitation Robotics*, pp. 43–46 (1997).

ABOUT THE AUTHORS

Noriyuki Tejima received the BS, MS and PhD degrees from the University of Tokyo, Japan, in 1984, 1986 and 1995, respectively. He was a Rehabilitation Engineer at the National Rehabilitation Center for the Disabled in Japan, from 1986 to 1996. Since 1996, he has been an Associate Professor of the Department of Robotics at the Ritsumeikan University, Japan. His research interests include rehabilitation robots, communication aids, human interfaces for assistive devices and psychological support systems for the elderly.