Usability of a Virtual Coach System for Therapeutic Exercise for Osteoarthritis of the Knee

Judith T. Matthews
Gustavo J. M. Almeida
Elizabeth A. Schlenk
University of Pittsburgh
Pittsburgh, PA, USA
jtmatt@pitt.edu

Reid Simmons
Portia Taylor
Carnegie Mellon University
Pittsburgh, PA, USA
reids@cs.cmu.edu

Renato Ramos da Silva
University of Sao Paulo
São Paulo, Brazil
renatopur@gmail.com

***Abstract*— Adherence to in-home exercise that complements outpatient physical therapy (PT) for osteoarthritis (OA) of the knee is less than ideal, with patients often performing exercises incorrectly or less frequently than prescribed. We are developing a virtual coach system designed to detect how individuals are performing their exercises and to provide individualized instruction and feedback in real-time. To assess potential end-users' responsiveness to the user interface prior to completing the entire system, we conducted a usability study using a Wizard of Oz approach with 10 middle-aged and older adults with knee OA. These individuals completed three pairs of therapeutic exercises commonly prescribed as part of an in-home regimen for knee OA while interacting with an avatar on a computer monitor as it offered instruction and feedback using different communication styles. Study participants were willing to wear wireless sensors while exercising and were comfortable receiving instruction and feedback via the virtual coach system. Though they found the avatar's guidance easy to follow, they were unable to differentiate its various communication styles. Nevertheless, they considered our virtual coach system potentially very useful for people performing therapeutic exercise on their own at home.**

***Index Terms*—physical therapy, virtual coach, robotics, home-based therapeutic exercise, usability**

I. Introduction

Osteoarthritis (OA), the most common form of arthritis, is the second leading cause of long-term disability among American adults [1]. Average age at onset is 40 [2], with prevalence greater among men under age 50, women age 50 and older, and non-Hispanic African Americans, compared to non-Hispanic whites or Mexican Americans. An estimated 9.2 million adults have symptomatic knee OA, clinically defined by the presence of symptoms and physical examination findings that include joint pain, crepitus (crackling feeling or sound in the joint), stiffness after immobility, and limitation of movement.

For an estimated 60% to 80% of persons with knee OA [3], the disease intrudes upon everyday life, limiting essential functions such as walking, going up and down stairs, transferring, and other activities of daily living [4,5]. Treatment focuses on reducing symptoms and improving function using an array of medications, physical therapy approaches, and surgical interventions, if necessary [6]. The personal consequences are important due to deleterious effects of pain and disability on individuals' socialization and mental health, physical function, financial independence, and quality of life.

Joint-specific therapeutic exercise for strengthening individual muscles or muscle groups, which in turn stabilize the knee [6] and improve agility and balance [7] has demonstrated efficacy in several randomized, controlled clinical trials [8-16]. Many individuals with symptomatic knee OA receive short courses of outpatient physical therapy, attending sessions one or more times per week over several weeks. They are typically instructed to perform therapeutic exercises at home between sessions and after discharge from treatment, with printed instructions and illustrations used to reinforce execution of the proper technique demonstrated in the clinic. Though laudable, these efforts provide no assurance that the therapeutic regimen will be performed as prescribed at home, either in terms of technique or frequency. Studies addressing adherence to home-based therapeutic exercise for knee OA have typically relied on self-report, a notoriously inaccurate method for ascertaining health behaviors, and either gathered insufficient information to draw any conclusion or revealed suboptimal participation (<75%) that decreases over time and results in loss of prior gains in comfort and function [13,17,18].

Many of the maneuvers comprising exercises commonly prescribed for knee OA as part of a home-based exercise regimen can be done incorrectly in a variety of ways. Mastering these subtle maneuvers, or achieving one's personal best in the presence of limited range of motion or discomfort, typically requires repeated demonstration and instruction to reinforce proper execution. In the outpatient setting the physical therapist provides this guidance, based on direct observation of an individual's exercise performance. At home, however, such nuanced assessment and intervention is not available, and the individual may well perpetuate errors, potentially causing harm or abandoning the exercise or the entire regimen altogether.

There has been a push to integrate technology into home exercise programs in an effort to improve patient motivation and increase adherence. Devices and systems that enable real-time capture of health behaviors, or ecological momentary assessment (EMA), have been shown not only to reduce distortion caused by recall bias by assessing phenomena through instantaneous reports of immediate experience [19], but also to motivate performance of desired health behaviors. EMA has been used successfully with adults with knee OA to track their post-exercise knee pain in a timely manner [20]. As part of a virtual coach system for cyclists, Eyck et al. [21] found that feedback on heart rate data provided verbally during daily training activities resulted in athletes being more likely to enjoy their exercise and more motivated to do so while performing in a more "healthy" range.

Research on wearable sensors to monitor daily patient activity and in-home exercise while preserving the individual's independence has been reported in several studies. Sensing approaches have included a biaxial accelerometer and gyroscope system to measure uniaxial flexion–extension angles in the knee [22]; an accelerometer-based setup to measure uniaxial joint angles (less costly in terms of price and computing time) [23]; triaxial accelerometers to classify everyday activities such as sitting, standing, walking, and climbing stairs [24,25]; triaxial accelerometers in combination with a handheld PDA device to track a person's movement during exercise, offer instruction, and provide feedback on different measures including the number of exercise repetitions completed and remaining [26]; and sensor placement on several parts of the body to recognize multiple activities of daily living [27].

Researchers investigating ways that technology can interact socially with people through avatars (animated "talking heads" on a computer screen) [28], conversational agents [29] and sociable robots [30,31] are finding it important to model social conventions [32], user intent [33], user perspective [34], and common ground between robot and user [35]. Our own work has found, in concordance with the work of others [36], that people react to social robots in much the same way as they react to other people. For instance, people react more positively to robotic systems that have faces [37] and can display emotion [38], and they tend to interact more with an avatar that appears to be happy [39]. Other research has evaluated how the "personality" of a robot can affect the quality and quantity of repetitive exercises [40,41] and demonstrated that matching the personality of the robot and user results in the best outcomes.

Especially relevant to the usability of our virtual coach system is the work by Kidd and Breazeal [42] and Torrey et al. [43]. The former team designed a sociable robotic "coach" to assist people in losing weight, and they made a deliberate effort to ensure that the robot would not be boring or annoying when offering guidance and feedback on recent behavior or when trying to integrate into the person's existing social support network. People using their coaching system adhered significantly better to their weight loss regimen [44]. The latter team investigated the effects of different linguistic strategies in help-giving robots. They found that adapting feedback to the user's level of competence in a task affected their performance and relationship to the robot [45].

II. Virtual Coach System

We are developing a virtual coach system that will use EMA methods to capture actual home-based therapeutic exercise performance among persons with osteoarthritis of the knee. Our fully integrated system will ultimately sense how an individual is performing each exercise, provide personalized instruction and feedback in real time to motivate adherence and execution of proper technique, adjust the pace and intensity of exercise to the individual's performance, and enable self-monitoring and sharing of progress with health care providers. While our colleagues Taylor et al. [46] are engaged in parallel efforts to identify the suite of sensors and develop the software algorithms for the perception and classification systems, we have focused on the feedback system.

We began by recording the conversation that occurred as the physical therapist (Almeida) on our team instructed a graduate student (without knee OA or a history of receiving physical therapy) in the proper technique for therapeutic exercises that would be prescribed for persons with knee OA to perform at home. We observed that the therapist's communication was variously nurturing, directive (or stern), and supportive (a mix of nurturing and directive). These recordings have informed the utterances and communication styles that we have incorporated into *Valerie*, the full-screen avatar, dynamically displayed on the computer monitor of our virtual coach system and depicted in Fig. 1. Our intent is for Valerie to evoke the therapist's vocabulary and phrasing when offering instruction and feedback, providing encouragement, and engaging in small talk, as well as his changing emotional expression and prosody, i.e., his rhythm and speech intonation.

Our next step was to observe potential end-users as they interacted with this interface and to garner their perspective before investing the considerable effort and resources required to develop and integrate the perception, classification, and feedback components of our virtual coach system.

III. Specific Aims

The overall purpose of this study was to learn the views of people with knee osteoarthritis regarding the usability of our virtual coach system, the distinguishability of various communication styles of our avatar, and the acceptability of wearing sensors while receiving instruction and feedback during therapeutic exercise. Specifically, we aimed to learn whether adults with knee OA could accurately differentiate Valerie's nurturing, directive, and supportive styles of expression; felt comfortable and secure using the virtual coach system; and were willing to wear wireless accelerometers while performing pairs of therapeutic exercises guided by Valerie.

Fig. 1. Sample facial expressions of "Valerie"

IV. Methods

Upon obtaining required human subjects approvals from our respective universities, we recruited 10 community-residing, middle-aged and older adults with knee osteoarthritis (OA) to use our virtual coach system individually during a single, two-hour session. Each session was audio and video recorded and conducted in an observation room equipped with a chair, padded exercise table, and one-way mirror in the Clinical Research Suite of the School of Nursing at the University of Pittsburgh.

Individuals were eligible who were 40 years of age or older; had a history of knee osteoarthritis; were capable of performing physical exercise while sitting, standing, and lying prone; were able to hear and see well enough to watch television or use a computer screen; and were cognitively intact (i.e., able to carry on a conversation without apparent confusion or difficulty with memory) and able to read and speak English.

After completing informed consent procedures, participants responded to questions regarding their demographic profile and experience with outpatient physical therapy, in-home therapeutic exercise for knee OA, and in-home therapeutic exercise for other conditions. Dressed in loose-fitting clothes and wearing comfortable walking shoes, they were equipped with wireless tri-axial accelerometers or sham sensors, depending on whether the former were being tested as part of development for the classification component, that were lightweight and approximately equal in size. The tri-axial accelerometers are manufactured by Bosch Sensortec. They measure 45 x 27 x 19 mm in size, weigh 22 grams, have a range of ±8g, and collect data at a sampling rate of 50 Hz. For our research purposes the accelerometers' packaging was custom built by colleagues at Bosch. Data acquisition software was developed in MATLAB. The accelerometers or sham sensors were applied to the participant's anterior thighs and shins using a self-adherent wrap material (3M™Vetrap™ bandaging tape) that does not stick to the skin.

A physical therapist (Almeida) demonstrated the proper technique for performing six therapeutic exercises which are commonly prescribed as part of an in-home exercise program that complements outpatient therapy for knee OA. These exercises are designed to enhance strength, flexibility, and balance; improve physical function; and/or reduce pain or discomfort associated with the disease. Participants performed each exercise after it was demonstrated, to confirm their understanding of the technique and to reveal their unique functional limitations imposed by knee OA.

The physical therapist then directed the participant's attention to our avatar Valerie, which was displayed on a nearby computer monitor positioned in order to be seen and heard easily during exercise. After asking the participant to talk with Valerie while being guided through the six exercises, the physical therapist withdrew from the observation room. Unbeknownst to the participant, the physical therapist was in the adjacent room unobtrusively observing the participant-avatar interaction through the one-way mirror while (as the Wizard of Oz, or "the man behind the screen") remotely prompting all of Valerie's utterances through a touch screen interface of his own with pre-defined options for each exercise pair and communication style. Other members of the team, including a nurse and an engineer, also observed from this adjacent room, intervening as necessary to ensure both the physical safety of the participant and proper technical operation of the virtual coach system.

After introducing herself, Valerie explained the procedures for the remainder of the session: She would coach the participant through three pairs of exercises for knee OA that would be done at the participant's pace, with no need to rush. She would provide ample time for rest between paired segments during which interval the participant would be asked to respond to a brief survey. The participant was encouraged to drink water as desired from a bottle on the desk.

Valerie reviewed step-by-step instructions for each exercise prior to showing a narrated video that depicted the physical therapist performing the exercise using proper technique. The participant was asked to perform the exercise as instructed; if unable to do so, Valerie would replay the video.

- The exercise pairs were randomly ordered, and each paired segment took approximately 10 minutes to complete. The exercises consisted of the following, as illustrated in Fig 2.

- Three sets of 10 repetitions of knee extension while seated and three sets of 30 seconds of quadriceps stretching while lying prone (or standing)

- Three sets of 10 repetitions of leg curls while standing and three sets of 30 seconds of hamstring stretching while lying supine on the exercise table

- Three sets of 10 repetitions each of reverse action hip abduction while standing and wall squats while standing

Valerie's communication styles were also randomly ordered across exercise segments to ensure that each participant experienced all styles. The communication styles were nurturing, directive/stern, or supportive (the combination of

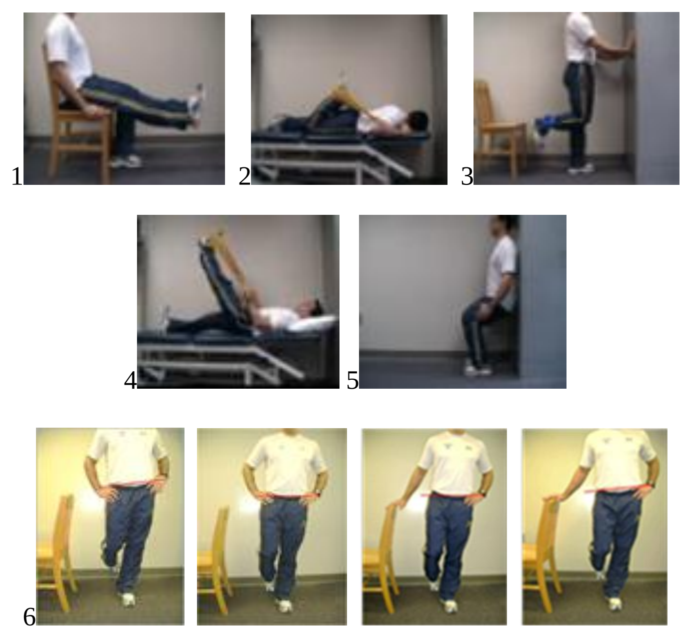

Fig. 2. Exercises: (1) knee extension; (2) lying quadriceps stretch; (3) leg curl; (4) lying hamstring stretch; (5) wall squat; (6) reverse action hip abduction

nurturing and directive/stern). Table I presents selected utterances representing each communication style. In addition to pre-defined options for each style, the physical therapist could compose comments or questions extemporaneously for Valerie to utter in the midst of an exercise being performed.

TABLE I. EXAMPLES OF COMMUNICATION STYLES

Style	Utterances
Nurturing	"You're doing well" "You're getting the hang of it. Nice job" "Wonderful – well done -- perfect!"
Directive/Stern	"Try harder" "Raise your leg higher" "You're not doing very well today"
Supportive	"You can do better, I know you can" "It's not easy, but it's worth it in the end" "Not quite perfect, but you're getting there"

Following each of the three exercise segments, participants were asked to respond to a brief investigator-developed questionnaire regarding the usability of the virtual coach system. On a scale from 1 (not at all) to 10 (extremely), participants rated how difficult it was to follow Valerie's instructions, how comfortable they were receiving instruction and feedback from her, how difficult it was to hear what she was saying, how acceptable it was to be told what exercises to do and how to do them, and how useful it would be to have a virtual coach like Valerie help people perform physical therapy exercises on their own at home. Upon completing the usability questionnaire after the third exercise segment, participants were asked how acceptable it was to wear wireless sensors while exercising. When data collection was complete, participants were debriefed about whether they had been wearing functional or sham sensors, and they were told that all actions by the virtual coach were prompted remotely by the physical therapist in the adjacent room.

V. RESULTS

Ten adults with osteoarthritis of the knee participated in this usability study, including 6 women and 4 men who ranged in age from 43 to 85 years (M=65.3; SD=13.2). The sample was predominately White (80%), well educated (60% > college education) and had a modest income (60% ≤ $50K household income) and health insurance that covered all or most of their health care expenses. The majority of participants (n=8) had previously received outpatient physical therapy, and 75% of these individuals (n=6) had been advised to perform a home-based exercise program as part of their treatment. Notably, they reported that it was moderately difficult (M=4.7; SD=3.5) to perform the exercises on their own, suggesting that adhering to the prescribed regimen at home was not easy. Among the five participants who had received physical therapy for any other conditions, all but one indicated that adhering to the therapeutic regimen at home was moderately difficult.

The entire sample completed all exercise segments without experiencing discomfort or fatigue beyond what they typically experienced with exercise. They found our virtual coach system usable and potentially very useful. The range of means across exercise pairs indicated that the directions given by Valerie were easy to hear (7.9-8.0) and follow (7.7-8.3), despite occasional difficulty understanding what she said. Participants were particularly comfortable (7.4-9.0) using the virtual coach system when performing the paired leg curl and hamstring stretching exercises (9.0). Being told by Valerie what exercises to do and how to do them was very acceptable (9.1-9.5), and there was strong consensus among participants that having a virtual coach system could be very useful in motivating people to perform physical therapy exercises on their own at home (9.3-9.6).

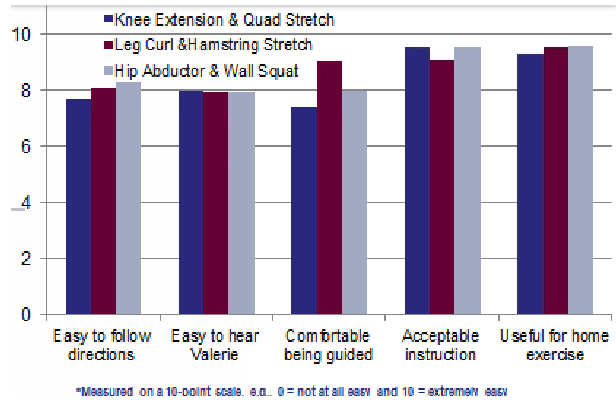

Fig. 3. Subjective ratings of the usability of the virtual coach system

Usability ratings did not significantly differ based on the ordering of exercise pairs or Valerie's communication style, except for how comfortable users were while performing the second exercise pair (p = .042). Similarly, participants were unable to distinguish among Valerie's various communication styles. They did, however, consistently verbally respond to the avatar when asked whether they understood specific instructions, felt discomfort or fatigue, or needed to rest or drink water. All participants were willing to wear the wireless accelerometers or sham sensors while exercising, though several remarked that smaller sensors would be preferable, especially when performing exercises in the prone position (i.e., lying on the abdomen).

VI. CONCLUSIONS

This investigation provided preliminary evidence of the usability of a user interface for the feedback component of a virtual coach system that we are developing. Despite our small sample size, we were able to gain valuable insight into how positively adults with knee OA reacted when presented with the verbal and facial expressions of an avatar that was, ostensibly, both cognizant of the quality and quantity of their performance and mindful of their stamina and comfort. Though our sample was limited to individuals with a single medical condition, we have no reason to believe that users with other functional impairments for which home-based therapeutic exercise is prescribed would respond differently.

We have no illusion that a virtual coach system with an avatar interface such as Valerie could substitute for the clinical judgment and sensitivity that a physical therapist provides when supervising therapeutic exercise performance among adults with knee OA. However, the reality is that physical therapists are not typically present in the home when such exercises are performed. We are encouraged that potential end-users cooperated fully with our Wizard of Oz evaluation, demonstrated their willingness to wear wireless sensors, and assessed our virtual coach system as largely easy to use, acceptable, and likely to be helpful in motivating themselves and their peers toward greater therapeutic exercise adherence.

Given the difficulty that study participants experienced in understanding some of the verbal expressions of the avatar and differentiating among its communication styles, further refinement of our feedback approach is warranted. We especially recognize the need to draw more heavily upon work in the fields of behavioral psychology and persuasive communication to craft a more effective avatar interface. The review by Wulf, Shea, & Lewthwaite [47], for instance, emphasizes the value of positive rather than negative feedback in motivating motor skill development, suggesting that any stern communication by the avatar is likely to be counterproductive.

Essential to successful deployment of an easy-to-use virtual coaching system is solving the many technical challenges that remain. These include integrating a sensor suite (e.g., accelerometers, depth cameras) that is capable of capturing nuanced exercise motions for an array of medical conditions, not just knee OA; building a software architecture that is highly adaptable to individual capabilities, performance targets, and display preferences; and enabling clinicians to monitor the user's progress and adjust performance parameters remotely.

Of particular interest is the extent to which participants appropriately responded verbally and with their exercise behavior to the instruction and feedback from the virtual coach, as a measure of their comprehension. Such analysis of our data goes beyond the scope of this paper, but it would provide further evidence to guide ongoing development of our virtual coach system.

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References

[1] R. C. Lawrence et al., for the National Arthritis Data Group, "Estimates of the prevalence of arthritis and other rheumatic conditions in the United States, Part II," Arth & Rheum, vol. 58, pp. 26-35, 2008.

[2] R. S. Fife, "Osteoarthritis: A. Epidemiology, pathology, and pathogenesis." In J. H. Klippel (ed.). Primer on the Rheumatic Diseases, 11th ed., Atlanta: Arthritis Foundation, 1997, pp. 216-217.

[3] S. E. Gabriel, C. S. Crowson, and W. M. O'Fallon, "Comorbidity in arthritis," Jl of Rheum, vol. 26, pp. 2475-2479, 1999.

[4] M. R. Maly, P. A. Costigan, and S. J., Olney, "Determinants of self-efficacy for physical tasks in people with knee osteoarthritis," Arth & Rheum, vol. 55, pp. 94-101, 2006.

[5] G. K. Fitzgerald, S. R. Piva, and J. J. Irrgang, "Reports of joint instability in knee osteoarthritis: Its prevalence and relationship to physical function," Arth & Rheum, vol. 51, pp. 941-946, 2004.

[6] C. Jinks, K. Jordan, and P. Croft, "Osteoarthritis as a public health problem: The impact of developing knee pain on physical function in adults living in the community: (KNEST3)," Rheum, vol. 46, pp. 877-881, 2007.

[7] K. D. Brandt, Diagnosis and Nonsurgical Management of Osteoarthritis, 2nd ed., Caddo, OK: Professional Communications, 2000.

[8] W. H. Ettinger et al., "A randomized trial comparing aerobic exercise and resistance exercise with a health education program in older adults with knee osteoarthritis: The Fitness Arthritis and Seniors Trial (FAST, JAMA, vol. 277, pp. 25-31, 1997.

[9] S. C. O'Reilly, K. R. Muir, and M. Doherty, "Effectiveness of home exercise on pain and disability from osteoarthritis of the knee: A randomized controlled trial," Ann of the Rheum Dis, vol. 58, pp. 15-19, 1999.

[10] M. V. Hurley and D. L. Scott, "Improvements in quadriceps sensorimotor function and disability of patients with knee osteoarthritis following a clinically practicable exercise regimen," Brit Jl of Rheum, vol. 7, pp. 1181-1187, 1998.

[11] B. T. Maurer, A. G. Stern, B. Kinossian, K. D. Cook, and H. R. Schumacher, "Osteoarthritis of the knee: Isokinetic quadriceps exercise versus an educational intervention," Arch of Phys Med & Rehab, vol. 80, pp. 1293-1299, 1999.

[12] H. Rogind et al., "The effects of a physical training program on patients with osteoarthritis of the knees," Arch of Phys Med & Rehab, vol. 79, pp. 1421-1427, 1998.

[13] M. E. van Baar et al., "The effectiveness of exercise therapy in patients with osteoarthritis of the hip or knee: A randomized clinical trial." Jl of Rheum, vol. 25, pp. 2432-2439, 1998.

[14] A. E. Mikesky et al., "Effects of strength training on the incidence and progression of knee osteoarthritis," Arth & Rheum, vol. 55, pp. 690-699, 2006.

[15] C. A. Thorstensson, E. M. Roos, I. F. Petersson, and C. Ekdahl, "Six-week high-intensity exercise program for middle-aged patients with knee osteoarthritis: A randomized controlled trial," BMC Musc Dis, vol. 6, http://www.biomedcentral.com/1471-2474/6/27.

[16] D. Evcik and B. Sonel, "Effectiveness of a home-based exercise therapy and walking program on osteoarthritis of the knee," Rheum Intl, vol. 22, pp. 103-106, 2002.

[17] W. J. Rejesky, L. R. Brawley, W. Ettinger, T. Morgan, and C. Thompson, "Compliance to exercise therapy in older participants with knee osteoarthritis: Implications for treating disability." Med & Sci Sports & Exer, vol. 29, pp. 977-985, 1997.

[18] K. S. Thomas et al., "Home based exercise programme for knee pain and knee osteoarthritis: Randomised controlled trial." BMJ, vol. 325, pp. 752-756, 2002.

[19] A. A. Stone and S. Shiffman, "Capturing momentary, self-report data: A proposal for reporting guidelines," Ann of Behav Med, vol. 24, pp. 236-243, 2002.

[20] B. C. Focht, V. Ewing, L. Gauvin, and W. J. Rejeski, "The unique and transient impact of acute exercise on pain perception in older, overweight, or obese adults with knee osteoarthritis," Ann of Behav Med, vol. 24, pp. 201-210, 2002.

[21] A. Eyck et al., "Effect of a virtual coach on athletes' motivation." In Proc of the 1st Intl Conf on Persuasive Technology for Human Well-being, pp. 158-161, 2006.

[22] H. Dejnabadi, B. M. Jolles, and K. Aminian, "A new approach to accurate measurement of uniaxial joint angles based on a combination of accelerometers and gyroscopes," IEEE Trans on Biomed Eng, vol. 52, pp. 1478-1484, 2005.

[23] W. Dong, I-M Chen, K. Y. Lim, and K. Goh, "Measuring uniaxial joint angles with a minimal accelerometer configuration." In Proc of the 1st Intl Conv on Rehab Eng & Assist Tech, pp. 88-91, 2007.

[24] S. H. Lee, H. D. Park, S. Y. Hong, K. J. Lee, and Y. H. Kim, "A study on the activity classification using a triaxial accelerometer.

In Proc of the 25th IEEE Eng in Med and Biol Soc Ann Intl Conf, pp. 2941-2943, 2003.

[25] D. M. Karantonis, M. R. Narayanan, M. Mathie, N. H. Lovell, and B. G. Celler, "Implementation of a real-time human movement classifier using a triaxial accelerometer for ambulatory monitoring." IEEE Trans on Info Tech in Biomed, vol. 10, pp. 156-167, 2006.

[26] J. Brutovsky and D. Novak, "Low-cost motivated rehabilitation system for post-operation exercises." IEEE Eng Med and Biol Soc, New York, pp. 6663-6666, 2006.

[27] L. Bao and S. S. Intille, "Activity recognition from user-annotated acceleration data." Perv Health, pp. 1-17, 2004.

[28] A. Powers, S. Kiesler, S. Fussell, and C. Torrey, "Comparing a computer agent with a humanoid robot. In Proc Intl Conf on Human-Robot Interaction (HRI), 2007.

[29] J. Cassell, J. Sullivan, S. Prevost, and E. F. Churchill, Embodied Conversational Agents. Cambridge: The MIT Press, 2000.

[30] C. L. Breazeal, Designing Sociable Robots. Cambridge: The MIT Press, 2000.

[31] H. Kozima, "Infanoid: A babybot that explores the social environment." In Socially Intelligent Agents: Creating Relationships with Computers and Robots, K. Dautenhahn, A. H. Bond, L. Canamero, and B. Edmonds (eds.), pp. 157-164, Kluwer Academic Publishers, 2002.

[32] T. Fong, I. Nourbakhsh, and K. Dautenhahn, "A survey of socially interactive robots." Robotics and Autonomous Systems, Special Issue on Socially Interactive Robots, vol. 42, pp. 143-166, 2003.

[33] N. Oliver, A. Garg, and E. Horvitz, "Layered representations for learning and inferring office activity from multiple sensory channels," Comp Vision and Image Understanding, vol. 96, pp. 163-180, 2004.

[34] G. Trafton et al., "Enabling effective human-robot interaction using perspective-taking in robots," IEEE Trans on Sys, Man, and Cyber, Part A, vol. 35, pp. 460-470, 2005.

[35] S. Kiesler, "Fostering common ground in human-robot interaction." In Proc of the Intl Workshop on Robots and Human Interactive Comm (RO-MAN), pp. 729-734, 2005.

[36] B. Reeves and C. Nass, The Media Equation: How People Treat Computers, Television, and New Media Like Real people and Places," Cambridge: Cambridge University Press, 1996.

[37] A. Bruce, "Decision theoretic approaches to human-robot social interaction," In Planning for the Real World, NIPS Workshop, 2003.

[38] R. Gockley, J. Forlizzi, and R. Simmons, "Modeling affect in socially interactive robots." In Proc of the Intl Workshop on Robots and Human Interactive Comm (RO-MAN), pp. 558-563, 2006.

[39] R. Gockley, J. Forlizzi, and R. Simmons, "Interactions with a moody robot," In Proc of the Human-Robot Interaction Conf, 2006.

[40] A. Tapus and M. J. Mataric, "User personality matching with hands-off robot for post-stroke rehabilitation therapy," In Proc of the Intl Symp on Exper Robotics (ISER-06), 2006.

[41] R. Gockley and M. J. Mataric, "Encouraging physical therapy compliance with a hands-off mobile robot." In Proc of Human-Robot Interaction, pp. 150-155, 2006.

[42] C. D. Kidd and C. Breazeal, "A robotic weight loss coach," In Proc of Natl Conf on Artif Intell, 2007.

[43] C. Torrey, A. Powers, M. Marge, S. R. Fussell, and S. Kiesler, "Effects of adaptive robot dialogue on information exchange and social relations," In Proc of the Intl Conf on Human-Robot Interaction (HRI), 2006.

[44] C. D. Kidd and C. Breazeal, "Robots at home: Understanding long-term human-robot interaction," In Proc of the Intl Conf on Intell Robots and Sys (IROS), 2008.

[45] C. Torrey, A. Powers A, S. R. Fussell, and S. Kiesler, "Exploring adaptive dialogue based on a robot's awareness of human gaze and task progress," In Proc of the Intl Conf on Human-Robot Interaction (HRI), pp. 247-254, 2007.

[46] P. E. Taylor, G. J. M. Almeida, T. Kanade, and J. K. Hodgins, "Classifying human motion quality for knee osteoarthritis using accelerometers," In Proc of the Intl Conf of the Eng in Med and Biol Soc, pp. 339-343, 2010.

[47] G. Wulf, C. Shea, and R. Lewthwaite, "Motor skill learning and performance: A review of influential factors," Med Educ, pp. 75-84, 2010.