Effect of Ultrasound on Mobility in Osteoarthritis of the Knee

A Randomized Clinical Trial

Judith Falconer, Karen W. Hayes, and Rowland W. Chang

Ultrasound increases soft tissue extensibility and may be an effective adjunct in the treatment of knee contractures secondary to connective tissue shortening. A randomized clinical trial was conducted to determine the effectiveness of ultrasound in relieving stiffness and pain in patients (age $\bar{x}$ = 67.5 years, SD = 13.0) who had osteoarthritis (OA) and a chronic knee contracture. Subjects received 12 treatments of exercise preceded by either ultrasound (n = 34) or sham ultrasound (n = 35) and a blinded evaluation at baseline, after treatment, and 2 months after treatment. MANCOVA controlling for baseline scores showed that there were no significant differences in knee active range of motion (ROM) (goniometry) or pain (visual analogue scale) between experimental and control groups. Possible explanations for the no difference finding involve dosage issues, muscle shortening, transiency of effects, and the effects of exercise. Paired t-tests revealed that both groups significantly improved ($p < 0.05$) in active ROM, pain, and gait velocity, and maintained improvement for at least 2 months. Although ultrasound may not contribute to the management of patients with chronic knee stiffness and OA, benefits of the exercise program and increased activity secondary to program participation probably influenced the overall improvement.

Osteoarthritis (OA) of the knee commonly causes limitation in knee mobility. Limited knee mobility alters joint alignment and strength, which may impair stability and gait. A knee limited by as little as 10° of motion may affect the biomechanics of joints both proximal and distal to the knee, which can increase the risk of additional dysfunction and pain. Patients with limited knee mobility must compensate with significantly increased energy expenditures in standing and walking [1] and therefore have lowered tolerance for these activities.

Limited knee mobility secondary to connective tissue shortening may respond to conservative therapy. Conservative therapies include a variety of stretching and strengthening exercises, heat, cold, traction, and splinting. Deep-heat modalities are frequently coupled with manual stretching procedures to enhance the effectiveness of exercise to lengthen soft tissues.

One means of producing deep heat, ultrasound, has been used for many years to enhance connective tissue extensibility based on evidence from animal research studies. Animal studies demonstrated that heat increased connective-tissue extensibility [2, 3]. Ultrasound produced heat deep enough to elevate temperature in swine joint structures 5°–8°C [4] and was selectively absorbed by tissues with high protein content such as bone and connective tissues [5]. Since ultrasound heats periarticular structures effectively [4, 6], it may be an effective adjunct in the treatment of joint contractures [7].

Clinical studies of the use of ultrasound to increase

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joint mobility in humans with osteoarthritis are inconclusive [8]. Ultrasound has been reported to be effective in increasing joint range of motion (ROM) in uncontrolled [9–11] or unblinded [12] conditions, and ineffective under controlled conditions when not combined with exercise [13]. This article is a report of a randomized, double-blind, sham-controlled, clinical trial that was conducted to test the hypothesis that ultrasound therapy with exercise is more effective than exercise without ultrasound in the treatment of chronic knee hypomobility in OA.

METHODS

Subjects

Study subjects were evaluated for eligibility and referred by physicians from the rheumatology, orthopedic surgery, geriatric medicine, and rehabilitation medicine practices of Northwestern University Medical School faculty. Criteria for inclusion in the study were

1. A physician diagnosis of OA of the knee that required the presence of knee pain, crepitus, and bony enlargement. Radiograph documentation of joint space narrowing and osteophyte formation was available for the majority of patients, but this was not a requirement for entry. Altman et al. [14] found that the clinical criteria used in this study were 89% sensitive and 88% specific for diagnosis of knee OA in this age population.
2. Limitation of at least 10° of passive motion in flexion or extension as measured by standard goniometry [15].
3. Ligamentous or capsular tightness as evidenced by a capsular endfeel [16].
4. Intact knee sensation to pinprick and temperature.
5. Chronic knee motion limitation defined by patient report as present for at least 6 months.
6. Physician referral to physical therapy and patient signature of informed consent.

Patients were excluded for conditions that are contraindications to the safe use of deep heat, including primary tumors or suspected metastasis to the lower extremity, severe arterial disease, hemorrhagic condition, and joint infection, or if they had ROM limitations due to bony involvement. Bony involvement was determined by a bony endfeel (bony joint "feel" in response to passive pressure at the end of range) as described by Cyriax [16].

Subjects who had total knee replacements with connective tissue tightness were eligible to participate in the study if they were at least 6 months postsurgery. Ultrasound is safe with metal implants because metal is thermally conductive and readily disperses the heat [3, 17, 18]. The cement used in total knee replacements absorbs no more heat than the surrounding bone [19, 20], and the ultrasound dosage used is too low to loosen the bond [21]. In patients with total knee replacements, however, additional variables such as the design of the prosthetic component, placement of the prosthetic component on the ends of the femur and tibia, relationship of the placement to the normal axis of motion in the joint, as well as ligament lengths may affect maximum range of motion. For these reasons, patients with total knee replacements were analyzed separately.

Equipment

Ultrasound was delivered by a Chattanooga Intellect 200 ultrasound unit that was calibrated by a medical equipment specialist. The unit operates at 1.00 MHz and has a 10-cm² soundhead. The effective radiating surface is 8.5 cm² ± 1.5 cm². The output meter reading accuracy is ±20% [22]. ROM was measured with a large, clear, plastic, 360° goniometer.

Assignment to Treatment

Patients were randomly assigned to either ultrasound treatment (experimental group) or a sham-ultrasound treatment (control group). Subjects who had bilateral knee OA received the assigned treatment to both knees. The knee studied was the knee with the least passive ROM or, if both knees were similar in passive ROM, the knee with the worst pain. Patients and evaluators were blinded to the assigned treatment.

Treatment Protocols

Subjects were treated by physical therapists at a private physical therapy practice staffed by faculty of Programs in Physical Therapy, Northwestern University Medical School.

Experimental Protocol The lower extremity was positioned in maximal extension or maximal flexion depending upon the end range that presented the most functional loss to the patient. Patients were given ultrasound to the knee (avoiding patella) using an aqueous gel as a coupling medium. Four areas (anterior, posterior, medial, and lateral) of ~100 cm² were sonated for 3 min each. Intensity of ultrasound was progressed from 0.0 W/cm² by increments of 0.1 W/cm² to a maximum tolerable dosage not exceeding 2.5 W/cm² for safety. Maximum tolerable dosage was defined as the dosage at which the patient reported a subjective sensation of warmth without pain. To maintain patient blinding, the physical therapist gave scripted instructions to all patients which stated that they may not feel warmth. Subjects were not asked directly whether they felt warmth; they were asked whether they felt any sensation such as rubbing, tingling, warmth, or discomfort.

Ultrasound treatment was followed by a 30-min exercise protocol for stretching. The exercise protocol included 5–15 min of passive stretch during the cooling period, tibiofemoral anterior–posterior and posterior–anterior grade-3 or grade-4 glides [23], and active ROM and isometric strengthening exercises. Quad sets, straight leg raises, knee to chest, bridging, and knee flexion–extension through full ROM exercises were done. Each exercise was repeated ten times. Each repetition was held for 5 s with a 5-s rest between repetitions. Patients received 12 treatments (2–3 times per week over 4–6 weeks), and were instructed in joint protection techniques and a daily home exercise program. The home exercise program was identical to the clinical exercise program, but excluding the glides.

Control Protocol The control group protocol was identical except that the ultrasound was a sham procedure. The ultrasound unit was turned on by the therapist treating the patient and appeared to function fully. The dials were lit and the patient could hear an audible beep at each sham increase in the dosage. Since the start button was not pushed, however, no energy was delivered to the tissues.

Evaluation Protocol

Patients were assessed at baseline, after treatment, and 2 months after treatment. Each evaluation required ~1 h and consisted of an interview and a functional evaluation performed by an experienced physical therapist. The interview contained questions regarding demographic characteristics, functional problems, and medical and prior knee treatment histories.

The functional evaluation consisted of measures of ROM, pain, and gait velocity. Active and passive ROM were measured by goniometry of the knee (flexion and extension) using the same evaluator at each assessment and a standardized protocol [15]. The goniometry testing positions (two joint muscles shortened over the hip) reduced the effect of muscle tightness as a primary cause of limited range. Goniometric measurement is the most common clinical method to quantify joint ROM and has established reliability and validity [24–27]. Knee pain was self-reported on a 10-cm horizontal visual analogue scale [28]. High reliability and validity have been previously reported [29, 30]. Gait velocity was obtained by recording the time a subject took to walk "as fast as possible" for 50 feet and converting the time to meters per minute (velocity).

The physical therapist recorded the maximum dose of ultrasound, patient comments, and any adverse reactions after each treatment. Patients completed at home and returned to the clinic a weekly home exercise program written report. The reports were used to facilitate and determine compliance with the home program.

Analysis

Multivariate analyses of covariance (MANCOVA) controlling for baseline differences in active ROM and pain were used to test the effect of ultrasound on posttreatment and follow-up values of the two main outcome variables, active ROM and pain. Since correlations between active and passive joint excursions were extremely high at baseline (0.97) and after treatment (0.98), only active ROM was used in the analysis. Chi-squared tests or *t*-tests were used to determine comparability of groups at baseline on demographic and descriptive variables. Paired *t*-tests were done to test for pooled group differences from baseline to posttreatment, and baseline to follow-up evaluations.

RESULTS

A total of 74 subjects met the study inclusion and exclusion criteria and were randomized to the experimental group ($n = 37$) and control group ($n = 37$); 69 subjects completed the experimental protocol ($n = 34$) or control protocol ($n = 35$). Five patients did not complete the study protocol (experimental group $n = 3$; control group $n = 2$) due to dissatisfaction with progress ($n = 2$, experimental group), illness ($n = 2$), or transportation problems ($n = 1$, control group). Eight patients had total knee replacements (experimental group $n = 6$; control group $n = 2$). No major complications were reported.

Characteristics of the experimental group and control group at baseline are shown in Table 1. The sample was predominantly older women who had moderate disease and were moderately limited in function. Mean age of the sample was 67.5 years (SD = 13.0) and mean length of knee stiffness was 83.4 months (SD = 122.1); 72% were women. Of the patients, 74% reported difficulty walking; 39% cited pain and 51% cited stiffness as a reason for difficulty walking. Eighty-seven percent reported difficulty stair climbing; 27%

TABLE 1

Descriptive Characteristics of Experimental and Control Groups at Baseline

	Experimental group		Control group		
	$\bar{x}$	(SD)	$\bar{x}$	(SD)	
Age (years)	69.4	(13.1)	65.7	(12.8)	NS
Chronicity (months)	77.2	(117.28)	89.6	(128.3)	NS
	%	(*n*)	%	(*n*)	
Female	76	(26)	69	(24)	NS
Noncaucasian	38	(13)	43	(15)	NS
Education <12 years	38	(13)	26	(9)	NS
Bilateral knee osteoarthritis	74	(25)	74	(26)	NS
Difficulty walking	76	(26)	74	(26)	NS
Difficulty stair climbing	88	(30)	86	(30)	NS

NS, not significant.

cited pain and 65% cited stiffness as a reason for difficulty stair climbing.

Ultrasound was not effective in improving active ROM or pain. No significant differences were found between experimental and control groups in active ROM and pain at posttreatment or follow-up evaluations. Means and standard errors at baseline, posttreatment, and follow-up evaluations of active ROM and pain are illustrated in Figures 1 and 2. The sample size provides adequate power (0.80) at α 0.05 for a one-tail test to detect a 5.3° difference in posttreatment ROM controlling for baseline differences. A ROM difference <5.3° would not be clinically meaningful.

Patients with total knee replacements were stiffer ($\bar{x}$ = 69.9 degrees, SD = 30.1) and has less pain ($\bar{x}$ = 4.1, SD = 3.7) at baseline and made slightly lower gains in active ROM ($\bar{x}$ = 3.8°, SD = 9.2) and pain ($\bar{x}$ = 1.7 cm, SD = 3.1) than subjects who did not have total knee replacements. Results did not differ when these patients were excluded, probably due to the small number (n = 8) of total knee replacement patients in the sample.

Although the experimental group subjects were not significantly different from control group subjects at posttreatment, when the data from both groups were combined, subjects were significantly ($p \leq 0.05$) improved from baseline to posttreatment and baseline to follow-up in active ROM, pain, and gait velocity, as shown in Table 2.

DISCUSSION

Ultrasound as delivered in this study did not enhance mobility in the knee. We found no differences between subjects treated with ultrasound and subjects treated with a sham-ultrasound procedure. Dosage, muscle shortening, transient effects, and exercise effects may explain differences between our results in humans and the evidence from animal studies.

Ultrasound dosage guidelines in humans are not well established. Extensibility requires that tissues be heated to the therapeutic range of 40°–45°C [6, 31]. Since a subcutaneous thermistor probe is the only objective measure of the deep tissue temperature, we do not know the deep tissues temperatures achieved. However, we did deliver a dose of ultra-

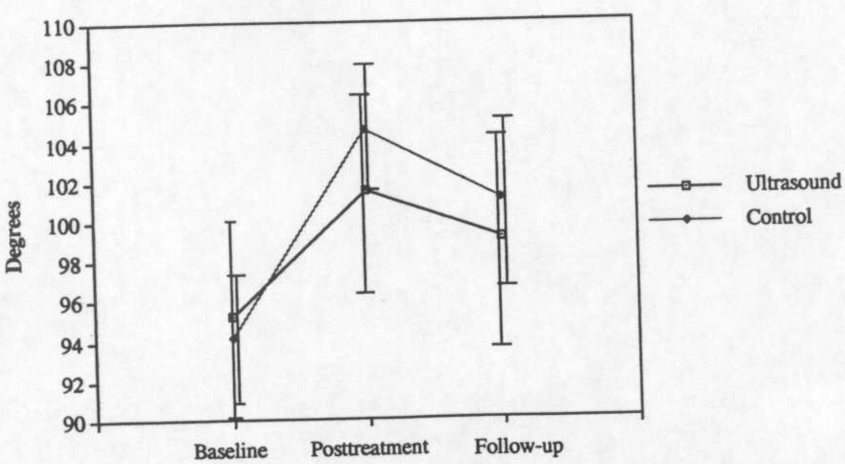

Figure 1 Means and standard errors for range of motion of experimental (ultrasound) and control groups at baseline, posttreatment, and follow-up evaluations.

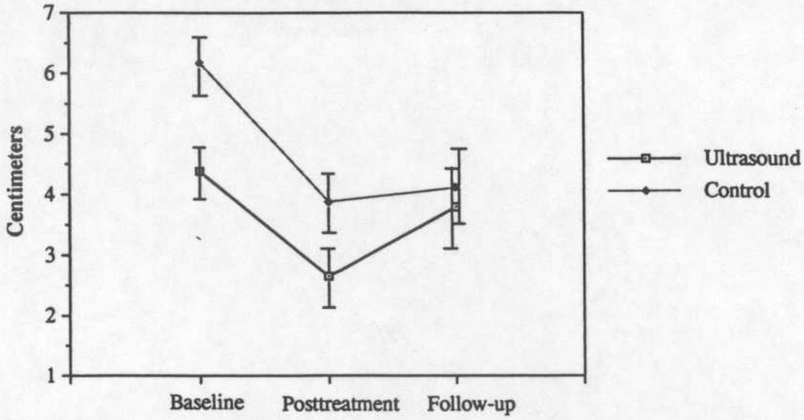

Figure 2 Means and standard errors for pain of experimental (ultrasound) and control groups at baseline, posttreatment, and follow-up evaluations.

TABLE 2

Means (Standard Deviations) for Baseline and Posttreatment Evaluations (n = 69) and Follow-up Evaluations (n = 56) for Combined Groups

Variable	Baseline $\bar{x}$	Baseline (SD)	Posttreatment $\bar{x}$	Posttreatment (SD)	Follow-up $\bar{x}$	Follow-up (SD)
Active range of motion (°)	94.7	(24.6)	103.1	(24.5)**	100.0	(26.2)**
Pain (cm)	5.3	(3.1)	3.3	(2.8)**	3.9	(3.1)*
Gait velocity (m/min)	66.0	(22.7)	74.2	(28.1)**	74.9	(24.4)**

*p < 0.05 (from baseline).
**p < 0.01 from baseline).

sound exceeding the level at which therapeutic effects were expected. In previous animal studies, ultrasound dosages needed to reach therapeutic temperatures have exceeded 1.5 W/cm² [2, 6]. The mean ultrasound dose that we provided was within therapeutic range at 1.7 W/cm², SD 0.3 (range, 1.1–2.2 W/cm²). Only seven of our subjects received dosages of <1.5 W/cm². Of these seven, four improved, two were not changed, and one was worse in ROM after treatment.

The dose that we delivered was also the maximum dose tolerable to the patient. If the subject reported any pain, the therapist held the intensity below the pain-producing level, even if no heat were perceived. Because the knee has a large amount of bone lying just below the skin with little soft tissue coverage, periosteal pain could have resulted from the ultrasound treatment at intensities insufficient to produce adequate heat. Higher intensities of ultrasound would be intolerable in humans, but a longer dose may be effective in achieving tissue extensibility.

We focused the ultrasound therapy on joint connective tissue structures because joint structures are the primary problem in osteoarthritis. If muscle shortening were involved, heating the muscle may have been more effective than heating the joint structures. However, ultrasound is not a good method for heating muscle. Muscle does not absorb ultrasound well because of its homogeneity and high water and low collagen content [5]. Muscle heating also involves treating a larger area than ultrasound can heat effectively.

Neither heat alone nor stretching alone effectively elongates connective tissues in rat-tail tendon [31]. Low-load, prolonged stretch during the heating period produces more extensibility than stretch applied after heating [32], and stretch maintained during the cooling period maximizes the retention of extensibility [31]. The experimental protocol was therefore designed to provide a low-load, prolonged stretch during the heating and cooling periods. Subjects were positioned at the end of available range (low load) during ultrasound treatment for 12 min and held in the stretched position as tolerated for 5–15 min of cooling. We do not know whether ultrasound and stretch had a transient effect on the joint structures, because we measured treatment effects after the patient received ultrasound and exercise. However, a transient effect would be clinically insignificant.

Ultrasound may have been effective, but unnecessary to achieve maximum ROM. Contractures in

OA are caused by soft-tissue tightening and bony obstructions. The active and passive exercises were designed to stretch the soft tissues (ligamentous, capsular, and muscular) and may be sufficient to release the soft-tissue component of the restriction. Any remaining restriction could be due to bony impingement that neither exercise nor ultrasound can improve.

Our results suggest, however, that exercise or participation in a structured activity program may benefit this population. Subjects in both groups significantly improved in the objective measures of ROM, pain, and gait: 77% of patients increased active knee ROM, 71% decreased knee pain, and 72% increased gait velocity. The general pattern of improvement did not appear to be affected by the patient's age, severity of pain, severity of ROM limitation, weight, the presence of bilateral knee disease, or a total knee replacement.

Attention placebo effects may have influenced the significant change from baseline to posttreatment. Study subjects enjoyed participating in the study, attended regularly, and complied with the home program. The proportion of subjects reporting change in walking and stair climbing from "problem" to "no problem" was significant ($p < 0.05$), but unrelated to improvements in ROM or pain. However, we have little clinical expectation that a chronic contracture would improve without an effective intervention, nor would we expect an attention placebo effect to maintain improvements through the follow-up period.

Benefits of exercise and/or increased activity from participation in a structured program may explain the posttreatment improvements. Compliance with the exercise program and increased activity secondary to program participation probably played a role in the achievement of posttreatment values. Attendance in therapy ($\bar{x} = 11.8$, SD = 1.3) and compliance with the home program ($\bar{x} = 88.1\%$, SD = 21.4) were comparable and excellent in both groups.

Continued compliance with the home program after treatment, and increased activity in the community secondary to perceived improvement in function, may explain the retention of change. The conditions under which continued compliance and activity would be expected were met in this study. According to Sackett et al. [33], continued compliance would be expected if the disease is significant, a definite diagnosis is made, the treatment is perceived as effective, and the patients are informed and willing participants. Continued compliance over 2 months would also be expected because exercise behaviors were partially reinforced [34], feedback was given on an intermittent schedule [35], and a follow-up evaluation within a period of 12 weeks was scheduled [36]. We think that patients maintained improvements through the follow-up evaluation because they continued to exercise and be more active, but we can not predict how long retention will last.

The improvements in active ROM, pain, and gait velocity may also have significantly improved safety, balance, and endurance for standing and walking. Gait velocities of ~74.6 m/min are needed to cross an intersection safely [37]. Our subjects improved in mean gait velocity from 66.2 m/min to near safe speeds of 74.2 m/min. Flexion contractures of 15° or more impair standing balance [38] and increase the energy and strength requirements of standing and ambulation [1]. Of our subjects, 78% improved in active knee extension, and 49% of the subjects had terminal extensions of <11° of limitation after treatment. The exercise program may have prompted a general increase in activity, greater attention and awareness of the knee and movement, and/or changes in activity behaviors that contributed to the overall effectiveness of both treatment protocols.

CONCLUSIONS

Patients with connective tissue knee contracture possess good potential for nonsurgical improvements in joint function. Although ultrasound may not contribute to the management of patients with chronic knee stiffness and osteoarthritis, exercise or structured activity programs may be beneficial. Until preventive measures are found, we need to determine the best methods of structuring, delivering, and reinforcing exercise programs.

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REFERENCES

1. Cerny K, Walker J, Perry J: Adaptations during the stance phase of gait for simulated flexion contractures at the knee. Phys Ther 68:797 (Abstr #R-112), 1988
2. Gersten JW: Effect of ultrasound on tendon extensibility. Am J Phys Med 34:362–369, 1955
3. Lehmann JF, Fordyce WE, Rathbun LA, Larson RE, Wood DH: Clinical evaluation of a new approach in the treatment of contracture associated with hip fracture after internal fixation. Arch Phys Med Rehabil 42:95–100, 1961
4. Lehmann JF, DeLateur BJ, Warren CG, Stonebridge JB: Heating of joint structures by ultrasound. Arch Phys Med Rehabil 49:28–30, 1968
5. Frizell LA, Dunn F: Biophysics of ultrasound. In Lehmann JF (ed): Therapeutic Heat and Cold, 3rd ed. Baltimore, Williams and Wilkins, 1982
6. Lehmann JF, McMillan JA, Brunner GD, Blumberg JB: Comparative study of the efficiency of short-wave, microwave, and ultrasonic diathermy in heating the hip joint. Arch Phys Med Rehabil 40:510–512, 1959
7. Gerber LH: Rehabilitation of patients with rheumatic diseases. In Kelley WN, Harris ED, Ruddy S, Sledge CB (eds): Textbook of Rheumatology, 3rd ed. Philadelphia, Saunders, 1989
8. Falconer J, Hayes KW, Chang RW: Therapeutic ultrasound in the treatment of musculoskeletal conditions. Arthritis Care Res 3:85–91, 1990
9. Soren A: Evaluation of ultrasound treatment in musculo-skeletal disorders. Physiotherapy 51:214–217, 1965
10. Griffin JE, Echternach JL, Price RE, Touchstone JC: Patients treated with ultrasonic driven hydrocortisone and with ultrasound alone. Phys Ther 47:594–601, 1967
11. Griffin JE, Echternach JL, Bowmaker KL: Results of frequency differences in ultrasonic therapy. Phys Ther 50:481–486, 1970
12. Aldes JH, Jadeson WJ: Ultrasonic therapy in the treatment of hypertrophic arthritis in elderly patients. Ann West Med Surg 6:545–550, 1952
13. Grynbaum BB: An evaluation of the clinical use of ultrasonics. Am J Phys Med 33:75–78, 1954
14. Altman R, Asch E, Bloch D, et al.: Development of criteria for the classification and reporting of osteoarthritis. Arthritis Rheum 29:1039–1049, 1986
15. Norkin CC, White DJ: Measurement of joint motion: a guide to goniometry. Philadelphia, FA Davis, 1985
16. Cryiax J: Textbook of Orthopaedic Medicine, vol 1: Diagnosis of soft tissue lesions, 7th ed., London, Bailliere Tindall, 1978
17. Gersten JW: Effect of metallic objects on temperature rises produced in tissue by ultrasound. Am J Phys Med 37:75–82, 1958
18. Skoubo-Kristensen E, Sommer J: Ultrasound influence on internal fixation with a rigid plate in dogs. Arch Phys Med Rehabil 63:371–373, 1982
19. Lehmann JL, Warren CG, Wallace JE, Chan A: Ultrasound: considerations for use in the presence of prosthetic joints. Arch Phys Med Rehabil 61:501, 1980
20. Krotenberg R, Ambrosome L, Moser R: Therapeutic ultrasound effect on high density polyethylene and polymethyl methacrylate. Arch Phys Med Rehabil 67:618, 1986
21. Lautenschlager EP: Professor of Biological Materials, Northwestern University, personal communication, 1986
22. Operating Manual Intellect 200. Chattanooga Corporation, Chattanooga, TN, 1984
23. Kaltenborn FM: Mobilization of the Extremity Joints: Examination and Basic Treatment Techniques, 3rd ed. Oslo, Norway, Olaf Norlis, 1980
24. Boone DC, Azen SP, Lin CM, Spence C, Baron C, Lee L: Reliability of goniometric measurements. Phys Ther 58:1355–1360, 1978
25. Rothstein JM, Miller PJ, Roettger RF: Goniometric reliability in clinical setting: elbow and knee measurements. Phys Ther 63:1611–1615, 1983
26. Enwemeka CS: Radiographic verification of knee goniometry. Scand J Rehabil Med 18:47–49, 1986
27. Gogia PP, Braatz JH, Rose SJ, Norton BJ: Reliability and validity of goniometric measurements at the knee. Phys Ther 67:192–195, 1987
28. Huskisson EC: Measurement of pain. Lancet 2:1127–1131, 1974
29. Scott J, Huskisson EC: Graphic representation of pain. Pain 2:175–184, 1976
30. Price DD, McGrath PA, Rafii A, Buckingham B: The validation of visual analogue scales as ratio scale measures for chronic and experimental pain. Pain 17:45–56, 1983
31. Lehmann JF, Masock AJ, Warren CG, Koblanski JN: Effect of therapeutic temperature on tendon extensibility. Arch Phys Med Rehabil 51:481–487, 1970
32. Warren CG, Lehmann JF, Koblanski JN: Heat and stretch procedures: an evaluation using rat tail tendon. Arch Phys Med Rehabil 57:122–126, 1976
33. Sackett DL, Haynes RB, Tugwell P: Clinical Epidemiology: A Basic Science for Clinical Medicine. Boston, Little, Brown, 1985
34. Logan FA: Fundamentals of Learning and Motivation, 2nd ed. Dubuque, Wm C Brown, 1976
35. Winstein CJ: Knowledge of results and motor learning: implications for physical therapists. Phys Ther 71:140–149, 1991
36. Care GRF, Harfield B, Chamberlain MA: And have you done your exercises? Physiotherapy 67:180, 1981
37. Chan SW, Conway LR, Walker JM: Older pedestrian can exceed velocities achieved in crosswalks. Phys Ther 68:858 (Abstr #R-411), 1988
38. Potter PJ, Kirby RL, MacLeod DA: Effects of simulated knee-flexion contractures on standing balance. Am J Phys Med Rehabil 69:144–147, 1990