Clinical Perspective

# The Influence of Subject and Test Design on Dynamometric Measurements of Extremity Muscles

In the context of broader discussions of clinical dynamometry, earlier reviews have raised concerns about the potential effects of variations in subject factors and test procedures on measurements. None, however, have dealt exclusively with these effects. We therefore reviewed more than 200 articles to evaluate in detail the effects of variations in subject factors and test procedures on measurements. Factors relating to subjects that affected measurements were age, gender, weight, athletic background, disability, and limb dominance. Test conditions that led to variations in measurements were range of movement in which values were obtained, type of contraction or movement (concentric, eccentric, isokinetic, isometric, isotonic), pretest procedures (warm-up and gravity-correction procedures, starting position, stabilization, axes alignment, lever arm length, preload, damp/ramp settings), test conditions (speed, test sequence, rest intervals, feedback), and type of data analysis (the data selected and how they are manipulated). In the majority of the publications, the authors failed to provide sufficient detail for accurate replication of test procedures or for comparison with other studies. We advocate that the factors identified in this review be included whenever measurements obtained with a dynamometer are reported. Effective development of normative data, formation of ratios, comparison of measurements across studies, and relating measurements with other performance criteria (eg, measurements of functional performance) all require descriptions of variables relating to subjects and testing. Similarly, meaningful use of these measurements in clinical practice requires consideration and documentation of these variables. [Keating JL, Matyas TA. The influence of subject and test design on dynamometric measurements of extremity muscles. *Phys Ther*. 1996;76:866–889.]

**Key Words:** *Dynamometry scores, Measurement error, Subject factors, Test conditions.*

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The importance and widespread use of dynamometry is evidenced by the large number of references to dynamometric measurements in the physical therapy literature. Since 1988, 30 to 40 publications per annum have reported findings based on data from electromechanical dynamometers. Electromechanical dynamometers have been used for many purposes, although data supporting these uses have not always been provided. Among the uses were:

1. To collect normative values for muscles and for various types of subjects.[1-14]

2. To classify muscle performance as normal or abnormal by comparisons with the performance of contralateral muscles,[15-18] with normative data,[19,20] or with muscle performance in a control group.[20-22]

3. To collect torque curves that might indicate whether pathology or characteristics specific to subject type were present.[19,21-30]

4. To establish the relative efficacy of various treatment and training regimens.[23,24,31-44]

5. To quantify exercise so that exercise regimens may be administered.[23,35,38,39,41,45-50]

6. To evaluate the effects of training or testing modes (eg, eccentric, concentric, isometric),[33,34,42,46,51-56] testing or training speed,[46,48,52,57-61] and duration of training.[24,39]

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7. To investigate factors that correlate with measurements. Measurements have been compared with muscle cross-sectional area measured by computerized tomography,[48,50,62-64] associated electromyographic activity,[38,65-72] type or location of electrical stimulation that causes force production,[73-75] physiological factors associated with muscle performance,[47,76-88] and biomechanical factors associated with muscle performance.[63,82,89,90]

8. To investigate the relationship between dynamometric measurements and measurements obtained with other tests.[23,24,31,34,42,44,82,91-93]

Electromechanical dynamometers are also in extensive clinical use.[94,95] Clinicians involved in the assessment or treatment of persons with disabilities use such dynamometers to determine the need for intervention, the

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This work was funded by the Harold Hopkins Award from the Hospital Superannuation Board, Victoria, Australia; the Felice Rosemary Lloyd scholarship; and the Australian Post Graduate Research Award.

*This article was submitted November 20, 1995, and was accepted March 20, 1996.*

extent of impairment, and changes in subject performance. Dynamometric measurements have also been used in courts of law as evidence of functional capacity.[94] Muscle performance throughout the tested range of movement can be examined with some dynamometers, whereas this was not possible with previously available instruments. Force produced at constant lever arm speed (isokinetic testing) and the speed achieved when resistance to movement is held constant (isotonic testing) can also be measured.

## Factors That Influence Measurements

Factors that may affect measurements need to be identified, and these effects need to be appreciated by clinicians and researchers. Changes in measurements should reflect changes in a subject's ability. If the procedures used influence measurements, test procedures need to be replicated when testing occurs on multiple occasions. Comparisons with published data are appropriate only when similar procedures are used. Similarly, when researchers obtain measurements under different conditions, comparison of results should be possible only if these differences have an inconsequential effect on the magnitude of the measurements.

In an early review on this subject, Mayhew and Rothstein[96] argued that measurements are influenced by several aspects of test procedure, including method of axis alignment, damp settings, and whether the measurements are corrected for the effects of gravity. They emphasized that the conditions under which measurements are generated must be defined if the measurements are to be meaningfully interpreted. Seventy-five percent of the publications we examined, however, were published after 1985, the majority of which were published after 1988.

A recent review of this topic[97] examined the literature on subject stabilization and test position, contraction mode, choice of equipment, and method of axis alignment. Our search of the literature, however, indicated a wider body of literature than has been considered in previous reviews, which provides evidence on a broader range of variables that could affect test outcome. We examined articles that presented information on measurement changes resulting from alteration of a single aspect of the testing circumstances. A subject or test factor was considered capable of influencing measurements when research findings indicated that systematic differences among mean values occurred when that factor alone was systematically altered. The reports reviewed were located using both manual and electronic searches of the literature. Electronic searches of *Index Medicus* were conducted primarily using combinations of the key words "dynamometer," "dynamometry," "strength," "muscle," "tests," "testing," "isokinetic," "normative," and "data."

## Subject-Related Factors

### Age

Dynamometric measurements of young and older subjects have been compared,[2,7,98–101] and measurements have also been reported for subjects in adjacent age decades.[5,13,102] These independent investigations all reported that forces decline with increasing age. This was true despite subject sample and methodological differences.

Details of test procedures to study the relationships between age and measurements were rarely found to be complete, a finding common to the broader body of literature reporting dynamometry testing. Omissions included descriptions of the rest intervals separating tests, how lever arm length was determined, how axes were aligned,[5,7,60,102] whether gravity correction was performed,[2,5,7,60,102] the type of warm-up used,[2,7,60,102,103] whether signal damping occurred,[7,60,102,103] whether feedback was given,[5,103] and the type of equipment used.[102]

Incomplete protocol description prohibits study replication. When test procedures cannot be precisely replicated, comparisons of reported measurements with measurements for subsequent tests of individuals may be misleading. In addition, the magnitude of age-related differences could be altered by differences in test design. At present, however, little evidence supports the possibility that experimental conclusions regarding the influence of subject age on measurements would differ if studies were replicated under conditions that varied from the conditions in the original studies. Presumably, the experimental conditions were standardized for each subject tested within a single investigation. It is improbable, therefore, that systematic alterations in test procedures caused the systematic changes in measurements associated with subject age consistently reported in these independent studies.

The reliability of obtained measurements was sometimes not reported in studies of aged muscle.[13,60,102] When reliability of measurements was reported, a variety of approaches were used. Some authors[2,5,101] preferred to use correlation coefficients, although it was not always clear whether the obtained correlation was for between- or within-session measurements.[5] Other approaches included reporting differences between measurements obtained in repeated tests as a percentage of those measurements[2,103] or reporting means and standard deviations of differences between scores obtained within and between sessions.[7] A discussion of these various options for presenting the error associated with measurements is beyond the scope of this review. Failure to ascertain the magnitude of error associated with measurements, however, does not necessarily negate conclusions based on data. The studies cited determined whether differences existed between measurements obtained for subjects grouped according to age. Findings of no significant differences, a statistical conclusion, have two possible explanations. One explanation is that measurements for the groups under comparison were similar. The other explanation is that although the groups were different, the magnitude of random error variability associated with measurements obscured systematic differences between groups of differing ages. The possibility would then exist that a more sensitive measurement, one with greater reliability, might detect such differences. When significant differences were detected between groups, these systematic effects were apparent despite random variability in measurements, however great. Regardless of the magnitude of random error associated with the obtained measurements, the magnitude of systematic effects attributable, in this case, to the age of subjects, was apparent. The need to establish reliability is important for many reasons.[104] In cases where statistically significant differences between means exist, however, the failure to first establish the magnitude of error associated with the measurements does not detract from the conclusions that group differences were found.

There are, however, some competing explanations for force declines associated with increased subject age. Because of the difficulty associated with longitudinal studies of the effects of aging on force, almost all investigations have compared groups of younger subjects with groups of older subjects. In order for differences between groups to be attributed to age, the groups need to be similar for other relevant criteria. One such variable is the weight of subjects tested.[3,60,105] At least for subjects under 33 years of age, weight has been positively correlated with torque production.[60,105,106] Differences in subject weight are unlikely to account for the effects of age observed by several researchers[2,5,101] because torque declined, even though the older subjects, on average, were heavier than the younger subjects. Although total body weight[5,101] may not reflect muscle mass, the same age-related torque declines were observed when subjects in different groups were matched for lean body weight[2,100] or when measurements were corrected for fat-free mass.[107]

A perhaps more viable explanation for age-related declines in measurements is that the activity levels of subjects of different ages also vary and therefore what is being observed relates to declining activity levels. Laforest et al[100] found that measurements of knee extension and knee flexion for both young and older tennis players were greater than measurements obtained for sedentary subjects who were matched for age, height, and lean body weight. Young tennis players, however, had greater force production compared with older tennis players, and young sedentary subjects had greater force production compared with older sedentary subjects. These results reinforce the likelyhood that age and activity level may combine to influence measurements, confounding the relative influence of each. The majority of studies on age-related changes in torque did not provide any indication of subject activity level.[2,5,7,13] Research that clearly differentiates the relative contribution of activity and aging to force measurements presents a substantial but important challenge.

Another explanation for the observed deterioration of torque with advancing age is that older subjects may require different test procedures in order to produce maximum values. Frontera et al[98] found that subjects aged from 45 to 78 years produced greater torques during a second test session than they produced during the first test session. Because only older subjects were tested, it cannot be determined whether the increases were unique to older subjects or generalizable to other test conditions, but the possibility remains that practice requirements for performance of the test may differ for subjects of differing ages. Similarly, it has not been established whether optimum warm-up and rest intervals differ for subjects of different ages.

Decreases in measurements of torque associated with advancing age have been observed. Whether age alone accounts for this deterioration or whether other factors that commonly occur in conjunction with aging are the cause is not clear. Investigations into age-related muscle changes provide some explanations for the observed force declines, including age-related decreases in the ability of muscle to generate tension,[99–101,108] decreases in muscle mass[99,101,109–111] decreases in proportion and selective atrophy of type II fibers,[107] and increases in nonmuscle tissue in muscle compartments.[101]

The magnitude of age-related changes, being specific to the sample tested, may have little application to tests of different individuals. In addition, the magnitude of age-related changes has been reported to vary with test conditions such as test position[102]; muscle group tested[2,103]; and whether the test was isometric or isokinetic,[7] or concentric or eccentric.[2] Despite differences in procedure, several researchers[7,100,101,107,112] have obtained force measurements for subjects who were in their seventh decade of life that were 70% to 80% of measurements obtained for subjects who were in their third decade of life. Rice et al[113] found an annual decline in measurements that averaged 2% across subjects aged 62 to 102 years. Although information regarding the reliability of the unorthodox measurement procedures used was not provided, the results were supported by other investigations.[114,115] Because many subjects were in nursing homes, the rate of decline probably reflects changes that occur in part as a function of having a relatively inactive lifestyle.

That significant differences in measurements have been observed when the same test procedures were applied to groups of subjects of different ages suggests that subject age should be considered when test results are compared. Clinicians and researchers comparing results for tests of individuals or groups with those reported in the literature should be aware that age differences among subjects under comparison can confound interpretation of measurement differences. Comparison of test results with those reported in the literature would be enhanced by knowledge of the mean, standard deviation, and range of ages of the subjects tested. Reports that detail only the range of ages of subjects[7,13,116–118] or that omit the range of ages[6,9,10,119–121] are commonly published. Some reports of "normative data" omitted any information regarding the age of subjects.[4,11,122,123] Additionally, the majority of published age-specific "normative data" is for groups spanning at least 10 years of age.[5,7,13,117,124] For those decades when strength gains or losses might be expected, research that attempts to narrow down the years when these changes more commonly occur may be useful. Additionally, interactions have been reported between age-related changes and other aspects of test procedures. Thus, for age-related normative data to be used for comparison with the results of tests of individuals, details regarding the test procedure used in the collection of such data must be available to clinicians.

### *Weight*

Body weight has been reported to have an influence on the magnitude of dynamometric measurements,[3,60,105] with heavier subjects tending to produce higher values than lighter subjects.[60,105,106] Although the existence of such a relationship has intuitive appeal, several factors should guide conclusions based on this body of literature. In none of the investigations cited were values corrected for the influence of gravity. For movements with gravity, measurements obtained for heavier subjects are likely to be artificially inflated because of the greater weight of their body segment. In addition, omissions in descriptions of protocols used were common and included the rest intervals between tests,[3,60] the warm-up procedures used,[60] the method used to align axes,[3,60,105] and whether the measurements were reliable.[3,60]

Furthermore, the method for determination of subject weight varied. Some researchers[3,60,105] although not specifying how subject weight was determined, presumably used total body weight. Other researchers[106] used a variety of weight estimates, including fat-free mass. Hoffman et al[125] correlated lean body weight with dynamometric measurements instead of using total body weight because they believed that total weight (ie, including fat) should correlate less well with subject strength. This argument may be logical, but the use of estimates of fat-free mass may be of less consequence when lean subjects are tested. Hortobagyi et al[106] found that correlations between weight and torque measurements for athletic subjects were similar, regardless of whether total body weight or fat-free mass was used. In contrast, results were found to be influenced by the method used to determine weight when "somewhat obese" children were tested.[126] Estimating lean body weight is more labor intensive than determining total body weight, and further research on the value of normalizing force measurements to lean body weight in preference to total body weight would appear to be beneficial. If total weight is reported, however, it may be appropriate to provide some evidence that subjects tested are not atypical with respect to percentage of body fat. In addition, torques expressed as a percentage of any measure of body weight should only be compared with measurements that were similarly calculated.

Subject weight has repeatedly been correlated to measurements of knee flexion and extension, and a range of coefficents that represent the relationship between the two factors have been reported.[60,105,106] As Hortobagyi et al[106] pointed out, the reported correlation coefficients must be interpreted cautiously. As the range of subject weights increases, the effect of the relationship between weight and torque measurements is likely to increase. If very heavy and very light subjects are tested, subject weight is likely to be a better predictor of performance than it would be for subjects of similar weight. The correlations obtained between weight and torque measurements for pooled male and female data,[105] for subjects spanning a large age range,[3] or for a mixture of trained and untrained subjects, therefore, may not represent the correlations expected when weight and torque measurements are correlated for subjects who are more homogeneous with respect to weight. Hortobagyi et al[106] found nonsignificant correlations between weight and dynamometric measurements of knee flexion and extension for a group of athletes who were relatively homogeneous with respect to age and training as well as weight. They concluded that factors other than muscle size may play at equally important roles in explaining differences in muscular strength.

Subject weight accounts for some of the variability in torque measurements, and this variability increases as the range of subjects' weights increases.[106] Muscle cross-sectional area partially accounts for variability in force measurements, and weight to some extent reflects muscle mass.[101] Researchers intending to provide useful data should report the weight of subjects. The range and distribution of force measurements obtained by researchers for subjects of similar weight would be of additional value to clinicians who want to compare the results of tests of individuals with published data.

### Interaction Between Gender and Weight

Investigations[1,2,125,127,128] indicate that torque measurements obtained with a dynamometer for male subjects exceed those obtained using the same protocol to test female subjects of similar age and athletic background. Comparison of torque measurements, therefore, should be made with consideration of gender.

It has been suggested that some gender-related differences can be eliminated by expressing measurements as a function of weight.[105,125] Hoffman et al[125] obtained torque measurements for bench press and leg press per unit of lean body weight for 30 male and 30 female cadets. Only the mean age of subjects was reported (male subjects, $\bar{X}$=20.2 years; female subjects, $\bar{X}$=19.4 years). Much of the detail regarding the test protocol was not reported. Additionally, the reliability of the measurements was not reported. The error associated with the measurements may have concealed gender-related differences in weight-adjusted leg-press values. Regardless of the magnitude of error associated with the test procedures, however, the systematic differences in weight-adjusted values attributable to gender were of sufficient magnitude to attain significance for bench press measurements. The authors concluded that when measurements are expressed per unit of body weight, leg strength differences between male and female subjects were within random variation, but the arm torques of men were higher. The authors argued that gender-related differences are not solely a function of overall subject size. Hoffman et al[125] proposed that circumference and bone-diameter measurements determine lean body weight.[129] These measurements are similar for men and women in the hip region but differ substantially in the shoulder region, suggesting that proportions of lean body weight by body region vary with gender.

Falkel[3] reported that weight and not gender was a critical factor in determining torque for isokinetic tests of plantar flexion. The results cannot be extrapolated to represent an absence of gender-related differences in mature adults, however, because two thirds of the subjects tested by Falkel were under 16 years of age. In addition, as the error associated with the obtained measurements was not determined, the failure to attain significance for gender effects could represent insensitivity of the measurements. Furthermore, replication of the Falkel test could be difficult as the authors failed to clarify how axis alignment was determined, whether gravity correction was applied to the measurements, and what rest intervals separated contractions.

Nicholas et al[117] found that "peak torque per body weight" for knee extension (tested at 60°/s), hip extension (at 30°/s), and hip flexion (at 30°/s) did not differ with gender. Differences were found, however, for knee extension (at 180°/s), knee flexion (at 60° and 180°/s), and shoulder extension and shoulder flexion (at 60° and 180°/s). Some reservation regarding findings of nonsignificant differences is warranted, given the small sample size tested and the fact that several subjects failed to complete some of the test movements. In addition, no indication of the measurement error associated with the test procedure was provided. If score variability was inflated in both groups by random variability, this may account for the failure of some of the observed differences to attain statistical significance. Nevertheless, however large the measurement error, the measurements were sufficiently sensitive to reveal a systematic effect of gender for weight-adjusted values for some of the muscles tested. This finding indicates that for some lower-limb muscles, gender differences may not be erased by weight adjustment of measurements and there is the possibility that gender differences in weight-adjusted measurements may not be uniform across different movements or test procedures. Again, the application of the results is limited by omissions in the protocol description regarding the rest intervals allowed between contractions; whether data were corrected for the effects of gravity; and how subject stabilization, axis alignment, and lever arm length were determined.

Given the conflicting research findings, gender-related differences in test results should be considered likely for all tests and possible for any weight-adjusted measurements. It therefore appears inappropriate to combine male and female subjects' weight-adjusted measurements prior to analysis because "when weight is statistically controlled for, there is no difference in lower-extremity strength between sexes."[105(p91)]

When interpreting the results of studies, caution should be exercised when statistical analyses reveal that no differences exist between groups. This finding may indicate that there is no difference between groups, or it may reflect statistical insensitivity in identifying an effect. Such insensitivity is influenced by the sample size, the effect size, and the magnitude of random variability in measurements. We believe that an indication of this problem exists when we see conflicting findings from authors.[5,102] Highenboten et al[5] found concentric peak torque/body weight ratios for knee extension tests at 50°/s in subjects aged 25 to 34 years to be greater for male subjects ($\bar{X}$=2.49) than for female subjects ($\bar{X}$=1.98). Fischer et al,[102] who calculated peak torque/body weight ratios for isometric knee extension tests in subjects aged 20 to 29 years ($\bar{X}$=2.8 and 2.1 for male and female subjects, respectively), found that forces produced by male subjects did not differ from forces produced by female subjects. The differences between mean values for male and female subjects appear to be similar in both experiments. The conflicting conclusions may be due to differences in measurement sensitivity, experimental design, or the statistics used to examine the data.

In summary, forces generated by male subjects generally exceed those generated by female subjects when male and female subjects are matched for age and athletic background. Thus, when measurements are reported in research reports, combining data from male and female subjects[91,130–133] may limit the value of the results. Some authors have reported that weight-adjusted lower-limb measurements from male and female subjects do not differ, whereas other authors have found differences for specific tests. We believe that conclusions cannot be generalized beyond the test conditions reported. We contend that when weight-adjusted measurements from male and female subjects are pooled for analysis, interpretation of results should include the consideration that gender differences may exist.

### *Athletic Background of Subjects*

The influence of participation in athletics on force measurements has been investigated in several ways. Measurements obtained when the same test conditions were applied to athletes and matched control subjects have been compared. Alternatively, force measurements of subjects pursuing different athletic endeavors have been examined. In addition, measurements obtained under particular test conditions have been compared with measurements obtained under different test circumstances of subjects with different athletic backgrounds. The results indicate that participation in athletics influences force production.* There are several factors, however, that influence the conclusiveness of many of these studies.

Although investigators who have compared measurements from athletes with measurements from matched control subjects or other types of athletes have usually compared subjects of similar ages, they have often not matched subjects with respect to weight.[134,137] Conclusions regarding the effect of participation in athletics on measurements have sometimes been based on tests of so few subjects[134,137] that the generalizability of findings must be made with caution. Many authors failed to report the reliability of measurements.[11,117,135–137] Although such an omission does not negate findings of group differences, it does limit confidence that test results would be similar if the investigation were repeated. Again, not a single report was sufficiently detailed to enable precise replication. Among the omissions were how axis alignment was determined,[11,100,117,135–137] whether measurements were corrected for the effect of gravity,[11,117,135] the rest intervals allowed between repetitions,[11,117] and how subjects were stabilized.[117]

Nicholas et al[117] compared test results for a small group of nonathletic subjects with the results of several earlier studies of athletic and nonathletic subjects. The table of mean values obtained for tests of different samples demonstrates the considerable overlap in measurements for athletes and untrained subjects. In addition, there appears to be marked variability among measurements, even for samples of presumably similar subjects. Sample differences may account for the range of reported mean measurements obtained in these independent investigations. Another possible explanation is that experimental procedures differed in each investigation. Examples of such procedural differences include the amount of rest allowed between tests, the type of warm-up permitted, the number of test repetitions used, and the type of stabilization used. Most reports failed to adequately define the test procedure used; thus, the reason for observed differences in measurements cannot be confidently concluded.

Alexander[1] tested concentric knee extension of elite sprinters and concluded that the sample tested produced torques that were substantially greater than those of the nonathletic subjects tested by Francis and Hoobler.[138] Although this conclusion may be true for the studies compared, the generalizability of these findings (ie, sprinters produce greater forces than do nonathletic subjects) is limited due to important differences in the two groups under comparison. These differences were in subject age, scale used for measurement, and test speed. Because age[2,5,7,13,102] and concentric test speed† have been shown to influence results, the differences in measurements between groups solely attributable to subject differences cannot be isolated. Therefore, although it may be true that sprinters produce greater forces than do nonathletic subjects, this has not been conclusively demonstrated and we certainly have little idea about the magnitude of this difference.

Although conclusions based on dynamometry tests of athletes is somewhat confounded by a lack of information regarding the test procedures, many investigations have in common the finding that athletes generate greater torques than do nonathletes. Although this finding may appear obvious, overlap of measurements for athletic and nonathletic populations occurs. If systematic differences between groups are to be attributed

* References 1, 62, 100, 117, 122, 134–137.

† References 2, 8, 14, 49, 58, 62, 65, 70, 87, 128, 139–145.

to the influence of athletic participation, the circumstances under which measurements are collected must be similar. This reinforces the need for researchers to clearly and adequately describe subject and test details if dynamometry is to provide definitive information regarding effects of this nature.

### Height of Subjects

Molnar and Alexander[146] found a positive correlation between knee and elbow flexor and extensor torques and height in children aged 7 to 15 years. This correlation was reported to be more consistent and potent than the correlations to age, weight, sitting height, biacromial diameter, or calf circumference. Tabin et al,[126] however, in tests of 10- to 15-year-old children, found height to be only "loosely" correlated with measurements, with stronger correlations between measurements and lean body weight. Again, differences in experimental procedure make the conflicting conclusions difficult to evaluate. These differences were in sample size, subject age, muscles tested, and possibly method used to determine body weight. Moreover, replication of either of these experiments may not be possible due to the limited description of test procedures. Neither research group reported the test range of movement, subject position for testing, type of warm-up, rest intervals between test repetitions, preload or damping used, or whether measurements were gravity corrected. Thus, the relationship between height of children and measurements for specific test conditions remains uncertain.

### Presence of Impairment

The influence of impairments on dynamometric measurements has been investigated by comparing measurements for an injured limb with those for a contralateral healthy limb.[15,18,43,44,63,147–149] These studies have found measurements for injured limbs to be lower than those for noninjured limbs. The results of these investigations therefore support the notion that dynamometric measurements can reflect anticipated weakness in an injured limb. There are, however, several factors that limit the usefulness of this research. Half of the reports inadequately documented the test procedures used.[18,44,63,148] It is impossible, therefore, to assess the technical competence of the research or to validate the results through replication or through application of experimental procedures. No reports included estimates of the magnitude of error associated with measurements. Although such an omission does not invalidate findings of lower forces for the impaired limb, confidence that research findings would be replicated if the investigation was repeated on another occasion would be enhanced by evidence of the temporal stability of measurements.

These results suggest that measurements obtained with a dynamometer are sensitive enough to reflect strength differences between limbs in individuals with unilateral injuries. These results do not, however, provide clinicians with information regarding the amount of difference between measurements for contralateral limbs that constitutes evidence of impairment. The claim has been made that differences between measurements for contralateral limbs of greater than 10% provide evidence of impairment or muscle imbalance,[18,25,63] but the evidence to support such a claim does not appear to be strong. Mira et al[18] made such a claim based on knee extension tests of 15 volunteers without any known impairment. A quadriceps femoris muscle strength index was determined for each limb for each subject. This index was derived by pooling an average of isokinetic and isometric measurements, although the mathematics used were not reported. Strength indexes between contralateral limbs differed by a mean of 6%, with a standard deviation of 4%. These results led the authors to conclude that a mean variation of more than 10% represents abnormal differences between limbs. The generalizability of the findings are limited by the following factors. There was no description of the protocol used. Not even the test speed used was reported. The type of measurement was not described. No argument was made for the use of pooled isokinetic and isometric values, and the sample was too small to be considered representative of the population. One standard deviation of values around the group mean was used to derive the 10% figure. If 95% confidence in the application of these findings is desirable, the estimate of between-limb differences based on this work would more appropriately be considered 14%.

Goslin and Charteris[4] tested the knee extension of 30 male and 30 female subjects. The dominant limb was defined as the limb producing the greater knee extension torques. Nondominant-limb knee extension torques were then reported as a percentage of dominant-limb torques. The mean percentage difference was 86.7% (SD=14.4%) for the male subjects and 81.2% (SD=10.7%) for the female subjects. The results of this study are difficult to interpret. In the absence of evidence of reliability of the data, it is impossible to argue that the source of the observed difference between two limbs was not measurement error. Most likely, the observed effect was a combination of both limb strength differences and measurement error. The generalizability of the findings is also questionable. Protocol description was limited, and no demographic information on subjects other than gender was provided. The results suggest, however, that measurements obtained on a single occasion can, in subjects without known impairments, differ between limbs by more than 10%.

Grace and colleagues' research[25] further supports the inadequacy of the 10% guideline. These researchers tested the knee extension and flexion of 172 high-school football players aged 15 to 17 years. Ipsilateral-contralateral imbalance was defined as a difference in the isokinetic measurements between sides of 10% or more, as calculated by dividing the difference between the side of the greatest magnitude and the side of lesser magnitude by the side of the greatest magnitude and multiplying the result by 100. Grace et al reported that imbalances of more than 10% were a frequent finding. Interestingly, no relationship was identified between percentage differences between measurements for opposite limbs and subsequent injury during the football season. Interpretation of this report is again confounded by the inadequate description of protocols and a lack of evidence for the reliability of the measurements.

Differences that can be expected when testing subjects without impairments need to be reported. Such reports need to include evidence of measurement stability, the conditions under which data are collected, the measurements used for comparison between limbs, and how percentage differences are calculated. A broad range of subjects, with adequate representation of different genders, ages, weights, and athletic backgrounds, might also assist the subsequent application of results to tests of individuals.

Expressing the lower value as a percentage of the higher value or the right-limb measurement as a percentage of the left-limb measurement may or may not be an appropriate approach to the provision of clinically useful information. Use of percentage differences between limbs is based on the assumption that stronger subjects without impairments can be expected to demonstrate greater absolute strength differences between contralateral limbs than weaker subjects without impairments and that the differences are meaningful. For example, if it is claimed that contralateral peak torque differences for knee extension tests of subjects without impairments are within 10%, a subject producing 200 N·m of torque during a right knee extension test would be considered unimpaired if he or she produced 180 N·m of torque during a left knee extension test. A subject producing 50 N·m of torque during a right leg test would have to produce 45 N·m of torque during a left leg test to be considered unimpaired. No investigations were found that examined the relationship between the magnitude of a subject's measurement and the expected differences between measurements for contralateral limbs. Another approach might be to determine the absolute magnitude of differences between measurements for contralateral limbs demonstrated by subjects without impairments.

The influence of impairment on measurements obtained with a dynamometer has also been investigated by comparing measurements from injured subjects with measurements from matched control (noninjured) subjects.[10,20,21,64,150] There are many difficulties associated with interpretation of the results of these studies. No reports included estimations of the temporal instability of measurements. Components of protocol design essential to experiment replication were frequently not reported. Omissions included whether data were corrected for the effect of gravity,[10] how axis alignment was determined,[21] and how subjects were stabilized.[21] In some reports, no description of protocols was provided.[20,64] In addition, whether the lower values obtained from the impaired subjects were different from those from the control subjects was not always clear.[20,64] Although most researchers selected control subjects whose age and weight were similar to those of the impaired subjects, or reported weight-adjusted data, it was not always clear how well control subjects and impaired subjects were matched for athletic ability.[10,21,64] Instructions given to subjects may also influence obtained measurements. Dvir et al,[21] for example, reported that persons with patellofemoral pain were instructed not to push through pain. The results therefore provide a comparison between the pain-free capability of persons with patellofemoral pain and the maximum capability of noninjured control subjects. In the other studies cited, instructions given to injured subjects were not routinely clarified.

Attempts to compare measurements from impaired subjects with those from unimpaired control subjects raises the issue of the usefulness of normative data. Even for subjects who are homogeneous with respect to age, weight, and athletic background, large differences in subject capability can be anticipated. Refinement in our understanding of the methods under which normative data can be collected that minimize the differences in measurements currently observed between subjects appears to be a prerequisite for useful comparative data.

Uncertainty still exists regarding the magnitude of difference between measurements for opposite limbs that constitutes evidence of impairment. Even more limited are attempts to define impairment and disability by comparison of measurements with normative data from nonimpaired subjects. Investigations into the possibilities for dynamometry as a diagnostic tool have been hampered by inadequate reporting of research procedures and failure to establish the reliability of measurements. Collecting usefully large amounts of data on injured subjects may prove a daunting task for any single researcher. With adequate documentation, however, research can be replicated, validated, and extended by other investigators. The opportunity to collate results of multiple investigations has the potential to yield a larger body of data that better represents measurement differences attributable to specific types of disability and to provide clinicians with guidelines for evaluating tests of individuals. Such an approach to construction of a useful body of data requires that test procedures and subject details be reported in sufficient detail to enable accurate replication of test conditions.

### *Limb Dominance*

Investigations into the influence of lower-limb dominance on muscle force measurements have used a variety of tests to determine limb dominance. Determination of lower-limb dominance has been made on the basis of hand dominance,[14,151] the limb used to kick a ball,[46,52,58,152] the limb used to kick a ball through two goalposts set 1.2 m (4 ft) apart,[142] the limb used to kick a ball through a doorway from a distance of 3 m (10 ft),[153] the stronger limb as determined by dynamometric testing,[4] the "preferred leg,"[121] or without specification of the criteria.[21,25,52,103,117,154] Lucca and Kline[155] attempted to develop a more elaborate test for limb dominance. Subjects were asked to perform five tasks, and the lower limb used to initiate each task was recorded. These activities were ascending stairs, descending stairs, kicking a ball, hopping, and picking up a pencil with the toes. The limb that initiated four out of the five tasks was considered the dominant limb. The protocol appears to be flawed by the crediting of dominance to the limb that initiated climbing as well as descending stairs, as the stronger limb might lead up but not necessarily down stairs. Unfortunately, preference as determined by this protocol was not correlated with other methods of identifying lower-limb dominance. This test identified the limb that was preferred for initiating an activity as the dominant limb. Another way to determine lower-limb dominance might be to identify the limb that is preferentially selected for demanding or enduring tasks. Further research into the comparability of the variety of procedures currently used for identifying lower-limb dominance appears to be warranted.

Investigations into the influence of lower-limb dominance on force measurements have dealt primarily with muscles that surround the knee joint.[‡] In general, results indicate that no differences are apparent when measurements for the dominant lower limb are compared with those for the nondominant lower limb.[§] Measurements for muscles other than knee flexors and extensors may provide additional insight into possible strength differences between dominant and nondominant lower limbs.

Limb dominance may influence the magnitude of upper-limb measurements. Hinton[16] found peak torque for shoulder medial (internal) rotation to be greater on the dominant side than on the nondominant side for pitchers. Shoulder extension has also been associated with greater measurements on the dominant side in pitchers, swimmers, and nonathletes.[124] In neither of these studies were data corrected for the effect of gravity. Without gravity correction, results could be confounded if the dominant arm was systematically heavier than the nondominant arm. It is unlikely, however, that the contribution by gravity accounts for the observed effects, as Hinton[16] found apparently similar differences between limbs when subjects were tested in a standing position and medial rotation was performed across gravity. Although neither Hinton nor Perrin et al provided evidence that measurements were reliable, at least on the single test occasion reported, systematic effects attributable to dominance were apparent regardless of the magnitude of error associated with the measurements. The method used to determine the axis of the shoulder movement was not stated in either report. Whether the alignment method was the same for each subject and not systematically affected by factors associated with the dominant limb cannot be determined from the reports.

The magnitude of dynamometric measurements, therefore, appears to be influenced by a number of subject factors. Clinicians or researchers wishing to compare measurements obtained from individual subjects with some criterion measurement should observe the age, gender, weight, athletic background, impairment, and possibly limb dominance of the subjects under comparison.

## Movement-Related Factors

### *Joint Angle*

Torques will vary depending on the joint angle at which data are collected.[18,156] Methods used to determine joint angle are neither standardized nor consistently reported. For example, in tests of muscles surrounding the knee joint, zero knee extension has been defined as maximal active knee extension,[157] full passive knee extension,[158] and full extension (active or passive not defined).[21,130,159] Sometimes, how joint angle is determined is not specified.[131,132,160] Wilhite et al[161] used goniometric measurements to designate 5- and 90-degree knee flexion, but they did not specify the structures with which the goniometer was aligned. It may be reasonable to propose that full passive and full active knee extension could lead to establishment of a tibiofemoral relationship at zero knee extension that differs by as much as 15 degrees. Verification of this proposal nevertheless awaits the definitive experiment. It would appear appropriate in the interim to at least report the method used in the determination of joint

‡ References 4, 14, 21, 25, 33, 52, 58, 103, 155.

§ References 14, 21, 25, 33, 52, 58, 103, 142, 155.

angle in order to facilitate replication of this aspect of the experimental method.

### *Muscle Action (Concentric, Eccentric)*

Isokinetic testing can be performed with concentric or eccentric contractions. Measurements for maximum concentric contractions of specified muscles differ from measurements of eccentric contractions,[23,26,162] with eccentric peak torque being greater than concentric peak torque.[‖] Effects observed in measurements obtained concentrically should not be assumed for eccentric test results. In addition, as test speed increases, concentric measurements tend to decrease and eccentric measurements tend not to change or tend to increase.[128] The ratio of concentric to eccentric measurements, therefore, will vary depending on test speed.[1,147]

Vyse and Kramer[56] investigated the effect of muscle action sequence on the magnitude of obtained measurements. They compared measurements obtained when elbow flexors were tested concentrically-eccentrically or eccentrically-concentrically. Eccentric tests that followed concentric tests resulted in peak torque measurements that were significantly lower (about 10%) than those produced using the eccentric-concentric sequence.

### *Mode (Isokinetic, Isometric, Isotonic)*

Dynamometers can be used to test muscles isokinetically, isometrically, or isotonically. These different test modes affect the magnitude and type of test measurements obtained.[3,57,87,144,165,166] Furthermore, the magnitude of the difference between isometric and isokinetic measurements has been reported to vary with test speed[143] and with the muscle group tested.[165]

Despite the knowledge that measurements vary with test mode, no research-based guidelines for clinical selection of test mode appear to exist. When clinicians test an individual, they must make a decision regarding the test mode to use. Evidence of impairment or change in performance indicated under the chosen test mode cannot be assumed for tests using optional modes. Until more information is available, clinical and research conclusions should not be extrapolated beyond the test mode used.

## Pretesting Procedures

### *Warm-up Procedures*

Most descriptions of test protocols include descriptions of whether subjects performed any kind of warm-up prior to testing, although exceptions to this are common.[#] Various kinds of warm-up procedures are reported, but the reasons for the use of one method of warm-up rather than another are not necessarily stated. Methods used for warm-up include an unspecified number of submaximal contractions[1]; several submaximal contractions[3,23,174]; between 2 and 4 submaximal contractions[**]; 5 submaximal contractions[5,46,130,134,147,177]; 10 submaximal contractions[36]; and a series of submaximal contractions (4,[157] 6,[178] or 10[159]), which successively approach maximal effort. Some authors have chosen a combination of submaximal and maximal contractions for warm-up (2 submaximal, 1 maximal[131]; 3 submaximal, 1 maximal[49]; 3–4 submaximal, 1 maximal[77,132]; 3 submaximal, 2 maximal[153,179]; 3 submaximal, 3 maximal[58,180]; 5 submaximal, 1 maximal[51]; 5 submaximal, 2 maximal[94]; 5 submaximal, 5 maximal[105]; 5–8 submaximal, then practice trials[5]; 8–12 submaximal, 2 maximal[181]).

Some authors have used more subjective approaches to the warm-up protocol. Examples of this include allowing subjects to repeat submaximal contractions until they felt ready to perform maximally,[1] until the subjects demonstrated an understanding of the procedure by exhibiting smooth torque curves,[80] or when the reproducibility in repeated tests was deemed by the researchers to be good.[37] Some authors[5,16,22,52,128,178,179] have used exercises or workouts on bicycle ergometers prior to dynamometric testing. Wilhite et al[161] had subjects perform three repetitions each of a modified hurdler's stretch for hamstring muscle flexibility and a prone stretch for quadriceps femoris muscle flexibility prior to testing these muscles. Prior to testing at a range of speeds, Montgomery et al[182] positioned the subject for testing and the dynamometer was set for continuous passive motion at 120°/s for 5 minutes.

Presumably, the primary aims of warm-up procedures are to ensure subject safety during testing and to facilitate stability of test data. If optimum warm-up requirements to achieve these goals exist, they clearly have not been identified. Few investigations have specifically addressed optimum warm-up requirements. Almost 2 decades ago, Johnson and Siegel[116] tested knee extension using three submaximal warm-up contractions and six maximal test repetitions. The first three maximal contractions showed an increasing linear trend, followed by stable data. The authors suggested, therefore, that under the test conditions reported, three submaximal and three maximal repetitions were required to establish data without systematic trends.

‖ References 1, 21, 49, 56, 71, 128, 144, 163, 164.

\# References 2, 15, 17, 24, 25, 31, 47, 48, 59, 65, 73, 74, 81, 89, 91, 102, 167–173.

** References 21, 52, 116, 128, 138, 140, 175, 176.

Similarly, Mawdsley and Croft[183] found that maximal efforts tended to increase following three submaximal warm-up contractions. When subjects had no submaximal warm-up trials, however, the first three trials appeared to vary less and the second trial was the highest. Mawdsley and Croft[183] therefore argued that measurements for the average of the first three maximal trials may be reduced following submaximal warm-up repetitions. They proposed that submaximal warm-ups may not provide the most appropriate type of practice for their test conditions. They also noted, however, that some subjects who did not perform submaximal trials prior to maximal trials experienced knee discomfort. This was not a complaint when submaximal warm-ups were used.

Kues et al[184] obtained knee extension torques for 10 female subjects on three separate occasions. Based on visual analysis of data, they concluded that two practice sessions facilitate maximum performances. Although preliminary in nature, their report provides guidelines for researchers who want to determine the stability of their data prior to experimental intervention. Despite evidence that suggests the need for determination of the warm-up requirements for the specific set of test conditions used, researchers generally fail to provide justification for the selected warm-up procedures or evidence that obtained data is without systematic trends.

### Subject Starting Position

Ample evidence has been provided that torque production is influenced by the position in which subjects are tested.[††] Although many investigators[102,128,130,145,185,186] failed to determine the temporal stability of measurements, the weight of evidence supports the likelihood that, when other test factors are held constant, changes to subject position alone can influence force measurements. The most probable explanation for this is that changes to the length of muscle affect muscle force and lever arms change throughout a muscle's range of motion.[187] For reported data to be a useful resource for comparison with tests of individuals, therefore, the subject position used during the collection of such data requires adequate documentation.

### Subject Stabilization During Testing

Optimum subject stabilization for testing has received little attention. Available information appears to be limited to tests of muscles around the knee joint. Hanten and Ramberg[140] compared thigh, pelvic, and trunk straps with no straps during concentric and eccentric knee extension tests. They found no difference between measurements obtained under maximum and minimum stabilization. In a similar study by Hart et al[174] of concentric knee extension, force measurements were found to increase when pelvic and trunk straps were added to thigh straps. Hanten and Ramberg[140] tested female subjects, whereas Hart et al[174] tested male subjects. Of perhaps greater importance, Hanten and Ramberg had subjects in both groups (stabilized maximally or minimally) grip the sides of the chair during testing, whereas Hart et al did not instruct their subjects to do so. Gripping the sides of the chair may have afforded similar stability to that offered by strapping. Patteson et al[188] evaluated the effect of strapping the contralateral thigh during knee flexion and extension tests. Subjects were asked to grip the sides of the chair during testing, and again no differences were found between measurements obtained under those conditions. Because so little can be confidently deduced regarding the influence of subject stabilization on force measurements, it should be assumed that different forms of subject stabilization have the potential to influence the magnitude of obtained values.

### Method Used for Axes Alignment

Alignment of joint and lever arm axes is required for interpretation of forces applied to the lever arm. When the axes are aligned, the limb and the machine act upon each other with the same moment arm.[104] If alignment of axes varies, lever arm lengths may differ.[189] Although most authors claim to align equipment and joint axes, methods used vary. For knee tests, the axis of the dynamometer has frequently been reported to be visually aligned with the axis of the knee joint.[87,132,140,182,188] Such a definition provides little guidance to aid replication of the procedure. We believe that it is more appropriate to define the anatomical landmark used to represent the changing axis of knee joint movement. Some authors have aligned the axis of the dynamometer with the lateral epicondyle,[52,152,159,184,190] a horizontal line through the femoral condyles,[103,191] or a point near the lateral epicondyle where a minimum of slippage of the resistance pad against the tibia occurs as the knee flexes and extends through a 90-degree arc of motion.[192] Others have failed to specify the subject axis.[5,102,193,194]

If the axis of the dynamometer is aligned with the lateral epicondyle when the knee is resting in 90 degrees of flexion, the axes can be several centimeters out of alignment when the knee is moved to full extension. In general, because research reports fail to include reports of the knee joint angle at which alignment was established, replication of the alignment procedures is not possible. An even more complex problem arises when attempts are made to align the axis of the dynamometer with multiaxial joints such as the shoulder joint. How the joint axis is approximated and the position of the joint when axes are aligned should therefore be reported.

[††] References 16, 89, 102, 118, 128, 130, 145, 185, 186.

### *Determining Lever Arm Length*

When knee extension is tested, the axis of the lever arm is aligned with an estimated axis of the knee. The resistance pad on the lever arm is then attached to the tibia. Methods used to position the resistance pad and to determine lever arm length vary.[103,157] In addition, the criterion used for determination of lever arm length is commonly not specified.[4,39,146,151,195]

The force applied to the transducer will vary with distance from the axis of the knee joint. The farther from the joint axis the transducer is placed, the less should be the force registered by the transducer during a maximal contraction. The equation force × distance should, however, produce a constant value for the torque that moves the tibia independent of the position of the resistance pad along the tibial lever arm. Thus, altering the location of the resistance pad should not, theoretically, affect torque.

Several authors have reported that torque is not independent of lever arm length. Otis and Gould[192] observed that during isometric knee extension tests using the Cybex® II dynamometer,[‡‡] the farther from the knee joint the resistance pad was placed, the greater were the torques recorded. Although Otis and Gould failed to correct torques for the effect of gravity, it is unlikely that this could account for the torque decrements associated with diminished lever arm length. At 90 degrees of flexion, the effect of gravity on torques would be negligible, and torque changes associated with altered lever length appeared to be similar regardless of whether knee extension was performed at 90 or 30 degrees of knee flexion. In addition, although the reliability of the measurements was not reported, systematic effects on torque that were attributable to lever arm length were demonstrated. Otis and Gould argued that the observed differences occurred because the torque generated around the knee is determined by the distance of the patellar tendon from the changeable axis of the knee joint. As this distance is influenced by the relative position of the tibia and the femur, differences in resistance-pad location that move the tibia relative to the femur would alter the effective knee torque despite forces applied through the patellar tendon being the same. Cadaveric investigations cited by Otis and Gould provide evidence that the magnitude of possible differences in location of the knee axis are sufficient to account for the observed torque differences.

The findings reported by Kramer et al[196] support the observation that torque is influenced by lever arm length. Using the Kin-Com® dynamometer,[§§] they measured the torque during concentric-eccentric knee extension at 60°/s using dynamometer arm lengths corresponding to 33%, 67%, and 95% of the distance from the estimated location of the knee axis to a resistance-pad placement that just contacted the dorsum of the foot. The torques produced at the 33% length were approximately 39% lower than those produced at the 67% length (or approximately 50%–55% of the 95% length torques), and the torques produced at the 67% length were approximately 10% lower than those produced at the 95% length (approximately 86%–90% of the 95% length torques). Kramer and colleagues hypothesized that these differences were due to the effect of lever arm length on alignment of the axes of the knee and the dynamometer, alteration in the angle of the tibia relative to the horizontal at different lever arm lengths, and subject inhibition due to discomfort as the resistance pad is placed higher on the tibia. No evidence was provided, however, that these hypothesized mechanisms could account for the large differences in torque found for the three lever arm lengths used. In addition, no attempt was made to justify disregarding the explanation provided earlier by Otis and Gould.[192] Taylor and Casey,[197] using the Cybex® II dynamometer, compared torques produced at 25% (5–10 cm [2–4 in]) or greater shortening of the lever arm with torques produced at maximum usable leg length. The results again support the argument that lever arm length influences torque determinations. Taylor and Casey recommended placing the resistance pad at the most distal usable leg length and disregarding the manufacturer's statement that torque production is independent of lever arm length.

For the conditions studied, shortening the lever arm appears to result in decreased torque recordings. Whether the torque measured for muscles that cross the knee joint may be affected in a meaningful way by small alterations (eg, 1–3 cm) of lever arm length such as may occur clinically due to inconsistencies in axes alignment or resistance-pad placement, however, remains to be determined. Twenty-five percent reductions in usable leg length affect the magnitude of torque measurements, but smaller reductions have not been reported. In addition, the proposed explanations for this effect have not been adequately studied to determine the relative influence of each explanation on observed torque differences. Furthermore, how methods used to determine lever arm length affect torque measurements when joints other than the knee are tested have not been investigated. Standardization and reporting of the technique used for determining lever arm length, therefore, appear to be necessary if systematic differences in torque measurements associated with this aspect of test setup are to be avoided.

‡‡ Cybex, Div of Lumex Inc, 2100 Smithtown Ave, Ronkonkoma, NY 11779.
§§ Chattecx Corp, 101 Memorial Dr, PO Box 4287, Chattanooga, TN 37405.

### Determining Preload

The preload or activation force is a preselected minimum force that must be applied to the load cell to initiate movement of the lever arm. The purposes of the preload are to prevent accidental initiation of lever arm movement and to allow buildup of force generated by the tested muscles so that maximum torque is achieved earlier in the test range of movement than under conditions of no preload. As test speed increases and the time to move through the test range of movement and achieve peak torque decreases, it is thought that the need for preload increases. Although measurements of peak torque appear to be unaffected by the presence or absence of preload, the absolute value of the preload has been reported to affect average torque measurements.[152,190] Reports[170,198,199] indicate that torque measurements in the initial portion of test movement increase as preload increases. This increase would seem to be predictable as those forces that are applied prior to achievement of the preload force are no longer recorded. If an average of torque recordings over the test range of movement is needed, the obtained value could therefore be expected to increase as preload increases. Consequently, Kramer et al[152] suggested that comparisons of torques should be based on comparable preload forces.

Although the optimal method for determining preload has not been addressed, three methods have been reported:

1. The same preload is used for all subjects tested. The magnitude of preload varies with the joint and movement tested. Examples for tests of knee extension include 25 N,[200] 50 N,[33,52,196] and 150 N.[201]

2. Preload is determined for each subject using a percentage of the maximum torque the subject is capable of generating under the test conditions. The obtained torque curve then arguably represents a similar proportion of that subject's effort.

3. Preload is a multiple of limb weight. Kues et al[184] used a preload that was 150% of the passive weight of the lower limb. This preload was apparently adequate to prevent accidental initiation of lever arm movement.

A logical argument for one preload determination method over another has not been made in the literature and warrants attention. The magnitude of preload has been shown to affect the magnitude of measurements that are averaged over the test range of movement. When protocol replication is desirable, the preload used should also be replicated and should be reported when protocol descriptions are published.

### Choice of Damp/Ramp Settings

During the initial arc of motion tested, the lever arms of some electromechanical dynamometers accelerate to reach the preset speed. The point at which the preset speed is reached may show a bump in the torque curve, commonly referred to as "torque overshoot."[104] Sapega et al[202] reported that overshoot can result in erroneously high torque measurements that occur as the machine arrests the inertia developed by the accelerating limb. These errors increase when large limb segments are tested, large amounts of torque are developed, or small ranges of movement are tested. The problem of torque overshoot has been dealt with by using a window of data,[203] damping of data,[104] and acceleration ramping.[204]

Using a window of data carries the limitation that, at high test speeds, torque overshoot oscillations may continue late into the range of movement.[202] Damping electronically modifies signals received such that torque recordings are filtered to minimize oscillations. The Cybex® II dynamometer allows damp settings from 0 (no damp) to 4 (maximum damp). Damp settings can have a dramatic effect on the magnitude of torque measurements. In addition, as damp increases, the recorded torque curve is shifted to the right.[104] If angle-specific measurements were the criterion used, the magnitude of such measurements would therefore be influenced by the damp selected. The Kin-Com® dynamometer does not have damp settings, but torque overshoot is modified by acceleration and deceleration rampings that can be set at low, medium, or high. These ramp settings put a ceiling on the amount of acceleration of the lever arm allowed by the instrument.

Rathfon et al[204] examined the effects of different acceleration and deceleration rates on torques produced by knee extensors tested at 90°/s. They concluded that the choice of ramping did not appear to have a meaningful effect on torque averaged over the whole curve nor did it affect peak torque. Their findings, however, must be confined to the protocol studied. Ramps selected for tests of stronger subjects, heavier body segments, smaller arcs of movement, or higher speeds may affect data differently. Rathfon et al[204] emphasized that the size of the window of data that represents constant lever arm speed varies with ramp setting. In their experiment, higher ramp settings resulted in a decrease in the test range of movement that occurred at constant lever arm speed. Higher rampings apparently resulted in greater fluctuations in lever arm speed before a constant speed was reached. They concluded that the practice of deleting a predetermined arc of motion from the beginning and end of the torque curve to eliminate acceleration and deceleration phases is not justified unless verified for the protocol in use. Thus, damping can affect the magnitude of the torque curve and of angle-specific measurements, and ramping can alter the size of the isokinetic window. Damp and ramp settings, therefore, should be reported when results are published.

### *Gravity-Correction Procedures*

The importance of considering the influence of gravity on dynamometric measurements has been argued by several authors.[104,158,178,205] Gravity-correction procedures increase measurements for movements against gravity and decrease measurements for movements with gravity. Gravity correction is needed if data will subsequently be used to form ratios.[206] Corrected values theoretically provide a better estimation of torque generated by muscles than do uncorrected values.

Gravity correction of measurements is most commonly accomplished in one of two ways. Limb weight at a single point in the test range of movement can be used to estimate limb weight at the horizontal. The weight of the limb at various points through range of movement can then be determined. These estimates of correction values are made based on the assumption that the passive weight of the limb acting on the transducer will be related to limb weight at the horizontal by the cosine of the angle of the limb to the horizontal. Alternatively, direct measurement of limb weight can be obtained as the limb is moved passively through the test range of movement. Although van der Leeuw et al[158] have demonstrated that passive forces acting during knee flexion and extension are linearly, not cosinally, related to joint angle, the effect on data due to selection of correction method has not been established. Nevertheless, it is common for authors to report having used gravity-correction procedures on their data, without indicating the method used.[||||]

If gravity were the sole source of passive restraint to knee extension, the passive torque curve for knee flexion and extension would be cosinal in shape. The fact that it is linear[158] suggests that other structures that attach to the tibia, such as the hamstring muscles and structures posterior to the knee joint, may be placed under increasing tension as the knee extends, resulting in forces being registered by the transducer that are not due to the effect of gravity alone. The recent work by Finucane et al[206] confirms that the position in the range of movement selected for weighing the legs will influence the correction values applied to measurements of knee extension. It is possible that this is a consequence of passive forces not attributable to gravity that act over the test range of movement.

Our investigations indicate that the method used to determine the angle of the limb relative to the horizontal at the position selected for weighing affects the magnitude and shape of the cosine curve that is subsequently constructed. Although the Kin-Com® user's manual advises "for correct gravity-correction calculations, it is assumed that the reference value (relationship to horizontal at the position selected for weighing) is correct," no information regarding how this angle should be determined is provided. Many researchers,[137,157,158,196,213,214] although not specifying the method used to determine the angle of the limb relative to the horizontal, imply that they use the joint angle as a measure of this angle. Because the joint angle represents the relationship between the tibia and the femur rather than the lower limb and the horizontal, this does not appear to be a logical practice. Other authors[123,177,190,204,206] appear to base estimates on the angle of the lever arm relative to the horizontal.

Given the potential for variability in the value used for the cosine curve construction, it appears that the best method for correcting measurements of passive forces that oppose or assist active contractions would be to measure the passive torque through the range of movement for each subject and then correct the active torque measurement at each angle using the passive torque measurement obtained at the same angle. Such corrections would include all passive forces registered by the transducer at different parts of the test range of movement and are not influenced by errors associated with the estimation of limb position relative to the horizontal at the point selected for weighing. Because these corrections involve manipulation of large volumes of data, however, they appear unlikely to be adopted by clinicians.

Until more information is available, whether data are corrected for the effect of gravity and the method used for these corrections should be reported. When cosine corrections are used, details should include the position selected for weighing and how limb position relative to the horizontal during weighing is determined.

## Test Conditions

### *Test Speed*

There is abundant evidence that the speed used for isokinetic testing influences the magnitude of torque measured.[**] Concentrically measured torque decreases as test speed increases.[***] Thus, obtained measurements should be considered speed-specific, and comparison of measurements should be restricted to those obtained at comparable test speeds.

[||||] References 8, 15, 21, 56, 78, 122, 127, 138, 145, 164, 166, 170, 182, 194, 207–212.

[**] References 11, 16, 17, 26, 51, 57–62, 124, 132, 137, 138, 143, 152, 153, 164, 166, 180, 215, 216.

[***] References 2, 8, 14, 49, 58, 62, 65, 70, 87, 128, 139–145.

Torques measured eccentrically do not appear to demonstrate as consistent a relationship to test speed. For eccentric knee extension, forces measured at 30°, 120°, and 270°/s have been reported to not differ significantly.[144] Similarly, the data provided by Hanten and Ramberg[140] indicate that eccentric knee extension force varies little and randomly with test speed. Eccentric elbow extension force also appears to be unaffected by test speed.[171] In contrast, eccentric elbow flexion force has been reported to increase as test speed increases.[70,171,187]

Which speed is selected for testing may be of clinical importance. Differences between measurements obtained from professional and amateur athletes have been found to be significant at low but not at higher test speeds.[11,62] Appen and Duncan[134] found no difference between hamstring/quadriceps femoris muscle ratios for distance runners and sprinters except at a test speed of 300°/s, when sprinters had a higher ratio than did distance runners. Kannus et al[217] found that subjects with 8-year-old partial anterior cruciate ligament tears showed decreased measurements for flexion of the injured limb compared with the uninjured limb, but only when tested at higher speeds. In a study comparing the strength of the injured limb with that of the contralateral uninjured limb, Kannus and Jarvinen[217] found that the relative strength deficit of the hamstring muscles of the injured limb increased with increased test speeds. Similarly, Prietto et al[43] found that impairment was speed-specific for knee extension torque in subjects with partial menisectomy, with the greatest apparent deficit occurring at the highest test speeds.

The speed used for testing has an important influence on the magnitude of force measurements. Comparisons between independently obtained sets of force measurements can only be justified for concentric tests at comparable speeds. Furthermore, conclusions based on force measurements obtained at a particular speed may not represent the conclusions drawn from force measurements obtained at a different speed.

### *Rest Intervals During Testing*

The rest interval separating test repetitions may influence force measurement. When a rest interval of 30 seconds interrupted reciprocal knee flexion and extension test repetitions, the torques produced were on average 5% greater than when test repetitions were performed without rests.[219] When no rest separates test repetitions, measurements may show a declining linear or curvilinear trend.[66,219,220]

The effect of no rest interval on the magnitude of forces may differ depending on whether muscles are tested eccentrically or concentrically. Gray and Chandler[181] tested subjects with 40 consecutive concentric or eccentric quadriceps femoris muscle contractions. Peak torque production for the eccentric tests was found to decline by an average of 0.3%, whereas peak torque production for the concentric tests declined 47.7%. These findings are supported by Tesch et al.[71]

The way in which subjects fatigue when tested with a no-rest protocol may be partially attributed to individual differences in muscle composition. Individuals with a high fast-twitch fiber composition appear to fatigue more and recover less than individuals with a high proportion of slow-twitch fibers.[76] Individual strength differences may also affect fatigue curves. Patton et al[220] found that male subjects with high strength fatigued most rapidly and female subjects with low strength fatigued least rapidly. Therefore, the rest interval requirements for stable data may vary for individual subjects.

Thus, it appears that no rest between repeated tests of the same movement results in diminishing test measurements. The magnitude of peak and averaged torque measurements, therefore, may be influenced by the rest interval provided between repetitions.

### *Type of Feedback Given to Subjects*

Feedback to subjects about their force production has been reported to affect measurements. Hald and Bottjen[105] found that visual feedback increased knee flexion and extension forces measured at 60° and 180°/s. Although measurement reliability was not established, systematic effects attributable to the provision of feedback were not concealed by the measurement error, however large. Feedback was given on either the first or second test occasion, which would appear to invalidate systematic effects attributable to occasion as a competing explanation for the increases. Although subjects produced greater torques with feedback, the differences appeared to be small. Baltzopoulos et al[221] noted increases in gravity-corrected knee flexion and extension forces when visual feedback was provided. The forces attained with feedback were greater when the test was conducted at 60°/s but not at 180°/s. The small sample size (n=10) may account for the apparently greater forces failing to attain statistical significance when feedback was used at 180°/s. Figoni and Morris[222] found that visual feedback given to 20 male subjects resulted in an approximately 12% increase in peak torque for knee flexion and extension tested at 15°/s, but no differences were found at 300°/s. Although the reliability of the measurements was not reported, the randomized application of feedback or no-feedback conditions over the two test occasions probably excluded systematic effects due to occasion or sequence from explaining the observed differences. The actual percentage of increase

**Table.**
Checklist for Reporting Test Procedures

| |
|---|
| Subject-related factors |
| Age |
| Gender |
| Weight |
| Athletic background |
| Disability |
| Dominance |
| Test-related factors |
| Pretest |
| Warm-up procedures |
| Subject starting position |
| Stabilization |
| Alignment of anatomical axis and dynamometer axis |
| Lever arm length |
| Preload |
| Choice of ramp, damp settings |
| Gravity-correction method and whether it was used |
| During Test |
| Speed |
| Rest intervals |
| Feedback |
| Joint angle/range of motion tested |
| Muscle action (concentric, eccentric) |
| Mode (isokinetic, isometric, isotonic) |
| Posttest |
| Type of data |
| Data analysis |

reported may not be particularly useful because the data were not corrected for the effects of gravity. Percentage improvements associated with feedback for measurements that have not been gravity corrected will not necessarily reflect those that might occur when gravity correction is applied.

Peacock et al[223] found that visual and auditory feedback enhanced knee extension force measurements. The authors did not report the test speed that was used, whether data were gravity corrected, or evidence of reliability of measurements. No systematic trends attributable to test occasion were noted. These limitations make the observed increases of approximately 10% difficult to interpret or apply. The random application of feedback or no-feedback conditions, however, lend credibility to the authors' conclusion that feedback was responsible for the observed increases.

Despite the various limitations of these reports, the evidence suggests that, at least for slow test speeds, feedback is likely to enhance force production. It is nevertheless the more common practice for authors to fail to reveal whether subjects were provided with feedback. As another potential source of systematic measurement variability, it would appear appropriate that the presence and nature of feedback should be documented when test procedures are described.

*Test Repetitions*

How many test repetitions are performed and which repetitions are selected for analysis may also influence the magnitude of force measurements. Murray et al[7] found that average torque was higher on the second of two consecutive isokinetic trials. Johnson and Siegel[116] found a linearly increasing trend in the first three test repetitions. Stratford[149] found a similar linear trend for knee extension peak torque measurements for both the injured and uninjured limbs of patients with anterior cruciate ligament reconstruction. Burdett and Swearingen[132] reported that peak values for knee flexion and extension tests were not reached until the second or third repetition. Kues et al,[184] based on visual analysis of data for knee tests, concluded that subjects should be tested using four maximal repetitions and the greatest measurement obtained should be used to represent the subjects' maximal effort. The importance of defining the number of test repetitions used is presumably accepted as it is one of the more consistently reported aspects of experimental procedure.

Whether data from the first or subsequent test occasions are considered also appears to affect the magnitude of obtained force measurements. Several authors[7,193,224] report that measurements obtained on a second occasion were higher than those obtained on the first occasion. The fact that measurements have been demonstrated to systematically vary with test occasion underlines the importance of establishing temporal stability of data.

## Data Analysis

Several performance measures have been presented in the literature. The most common of these measures are the maximum (peak) torque produced from a series of repetitions, peak torque averaged across repetitions, the average torque produced during a single repetition or averaged across repetitions, average or maximum work and power, and angle-specific torque (torque selected at a specified joint angle). Experimental conclusions based on one particular type of measurement may not necessarily apply if other kinds of measurements are used. To ensure reproducibility of test procedures, therefore, it is important to clearly describe the measures used and how they were manipulated in the data analysis.

## Conclusion and Recommendations

The review indicates that dynamometric measurements are affected by many factors that are an unavoidable part of test procedure. Movement-related variables, pretest procedures, test conditions, data-analysis methods, and subject factors (Table) were all found to affect force measurements. These systematic effects indicate cause for concern over the exact procedure applied to collect data. In this respect, our analysis confirms and extends issues raised by previous reviews.[96,97]

These issues are pertinent to a wide range of research and clinical applications: when normative data are reported, when ratios are generated, and when measurements are correlated to other criteria or compared across studies. Clinicians who apply normative data or ratios to tests of an individual must be able to replicate the protocols used in normative studies. Similarly, comparison of measurements for repeated tests of an individual requires replication of test conditions if confounded interpretation is to be avoided. In addition, the reliability of clinical assessment cannot be assumed to be comparable to that published, unless protocol variables are comparable.

Yet, despite more than a decade of publications indicating systematic biases in test findings due to particular protocol variations, the majority of research publications in this field do not provide sufficient protocol or subject descriptions to allow replication of test procedures. Pitetti,[212] for example, claimed that the protocol described for testing elbow and knee flexion and extension could be used for job assessment and rehabilitation purposes. The protocol description, however, omitted several aspects shown to influence data: how gravity correction was performed, the damping used, the preload used, how axes were aligned, how lever arm length was determined, whether feedback was given to subjects, the range of joint movement tested, what kind of rest separated repetitions, and the isokinetic window used for data analysis.

Factors that influence force measurements were identified when change in the test condition under examination produced differences in test results. However, when no differences in test results were reported despite alteration to test conditions, the conclusion about the influence of the factor in question is equivocal. The lack of meaningful differences indicates either similarity of measurements under the compared test conditions or statistical insensitivity. Such insensitivity increases as sample size diminishes, and small sample sizes were a common feature of the publications reviewed. The insensitivity also increases as random variability in obtained measurements increases. This random variability could be influenced by experimental method. In this respect, it is important to note that the majority of publications examined omitted either essential information about test procedures or information about the magnitude of measurement error. A major implication of the arguments presented, therefore, is that protocol and subject factors need more extensive documentation than is typical at present. In general, it seems reasonable to suggest that until additional information is made available, at least those factors listed in the Table should be reported.

Another major implication is that some standardization of test methods used may prove advantageous, but further research is needed to guide that process. As this review showed, in current practice test procedures vary considerably, making it difficult to determine why experimental conclusions conflict. Many of the research questions that remain unanswered, such as the effect of gender on weight-adjusted measurements or the relationship between height and measurements for children, might have been resolved by now if comparison of results had been facilitated by similar experimental procedures. Of great additional importance, data on subjects with impairments, which are often difficult to collect in large volumes, could be collated to form a more representative database if experimental conditions under which data were collected were standardized.

Standardization of protocols is dependent on knowledge about those factors that influence measurements. This review indicates the need for further research into the factors that influence measurements. Although the literature has already identified many test factors that appear to systematically influence measurements, additional information is needed regarding optimal test procedures. Outstanding questions identified by this review include the way in which the method used for aligning axes affects measurements, how lever arm length and preload should be determined, the influence on measurements when different methods for gravity correction are used, optimum rest intervals and warm-up requirements, and whether feedback should be used. Additional research on how measurements are affected by subject factors such as age, weight, and determination of lower-limb dominance is also indicated. In particular, it may be necessary to obtain norms for specific subgroups of subjects if normative data are to be used to interpret the results of tests of individuals in the clinic.

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