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IMPORTANCE OF UPPER-LIMB INERTIA IN CALCULATING CONCENTRIC BENCH PRESS FORCE

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Abstract

The purpose of this study was to investigate the influence of upper-limb inertia on the force-velocity relationship and maximal power during concentric bench press exercise. Reference peak force values (F_{peakp}) measured with a force plate positioned below the bench were compared to those measured simultaneously with a kinematic device fixed on the barbell by taking (F_{peakt}) or not taking (F_{peakb}) upper-limb inertia into account. Thirteen men (27.8 \pm 6.4 years, 184.6 \pm 5.5 cm, 99.5 \pm 18.6 kg) performed all-out concentric bench press exercise against 8 loads ranging between 7 and 74 kg. The results showed that for each load, F_{peakb} was significantly less than F_{peakp} ($P < 0.0001$), whereas no significant difference was found between F_{peakp} and F_{peakt} . The values of maximal force (F_0), maximal velocity (V_0), optimal velocity (V_{opt}), and maximal power (P_{max}), extrapolated from the force- and power-velocity relationships determined with the kinematic device, were significantly underestimated when upper-limb inertia was ignored. The results underline the importance of taking account of the total inertia of the moving system to ensure precise evaluation of upper-limb muscular characteristics in all-out concentric bench press exercise with a kinematic device. A major application of this study would be to develop precise upper-limb muscular characteristic evaluation in laboratory and field conditions by using a simple and cheap kinematic device.

KEYWORDS

force-velocity relationship, maximal power, ballistic movement

INTRODUCTION

The force-velocity relationship and explosive maximal power output (P_{max}) are widely used parameters in studying the mechanical characteristics of muscles or muscle groups during cycling (1,26,32)

and single- (22,30) or multiple-joint lower-limb extension (25). In explosive events, neuromuscular and mechanical factors, including maximal lower-limb force and power, may contribute to final performance (31). Several authors have described significant relationships between P_{max} and explosive event performance in track cycling (12) and sprint running (17). Maximal lower-limb strength has been related to sprint running performance (4,40). Hautier et al. (13) reported that optimal velocity (V_{opt}) (i.e., the velocity corresponding to P_{max}) correlates to the percentage of fast twitch muscle fibers in the vastus lateralis, and V_{opt} has been related to track cycling performance (12).

A prime objective in training is to identify the best training program and conditions to enhance the athletes' performance (36). Athletes usually train at a certain percentage of the maximum weight they can lift once with proper form and technique (1RM). Load, however, is not the only parameter taken into account in strength training programs, especially for explosive events. Several authors have shown that training with heavy loads enhances strength, whereas training with light loads enhances power production (5,15,16). Both qualities are important in performance. It has previously been shown that maximal power is obtained for light loads (i.e., high movement velocity) (2,25,28). A precise determination of the load associated with P_{max} could be useful for improving training efficiency. This suggests that muscular characteristic evaluation for athletes involved in explosive events should concern maximal force and maximal power production.

Maximal power can be determined by using kinematic systems, which enable muscular parameters to be assessed in terms of lifted load displacement during squat (14,25) or bench press exercise (6-11,14,27). To calculate force from kinematic data accurately, the total inertia of the mechanical system must be determined accurately (i.e., the mass of the lifted load plus the inertia of the levers and body segments). Several authors have shown that the force produced during single-joint extension of the lower limbs is underestimated if lever arm and leg inertia are not taken into account (20,23,39), and an underestimation of P_{max} , maximal force, and maximal velocity extrapolated from the force-velocity and power-velocity relationships can result (23).

In various bench press studies (6-11,14,27), force was calculated on the basis of load only, without taking into account the total inertia of the system (i.e., load plus upper-limb mass). This means that the upper-limb mass and the effort required to accelerate the upper limbs were neglected, and this disregard led to an underestimation of maximal power production. This

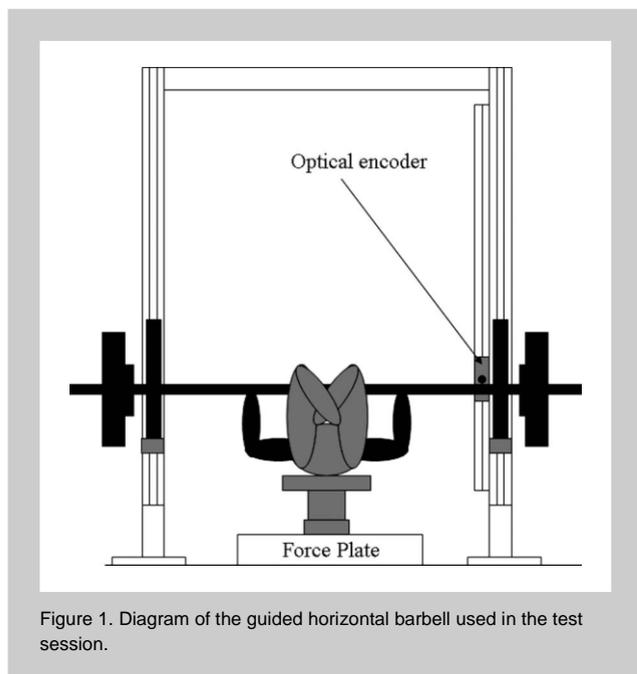
methodological bias would explain why mean maximal force values obtained in groups of team-sport players using kinematic devices (11,14) were systematically less than those measured with a force plate (18,34,35,37).

It would be of interest for throwers or team-sport players to assess upper-limb muscular characteristics. The purpose of this study was twofold. First, it sought to determine the influence of upper-limb inertia on bench press force calculation by comparing peak force values obtained directly with a force plate to those calculated from barbell displacement recorded with a kinematic system taking upper-limb inertia into account and not taking it into account. Second, the influence of inertia on the force-velocity and power-velocity relationships was examined to propose a valid protocol to evaluate upper-limb muscular characteristics accurately.

METHODS

Experimental Approach to the Problem

Subjects came to the laboratory once. During the session, a series of bench press movements was performed against 8 loads (7, 15, 24, 34, 44, 54, 64, and 74 kg), with simultaneous force plate and kinematic recording (Figure 1). The force-velocity and power-velocity relationships were determined from the kinematic data. Correlations between results under various measurement conditions were analyzed statistically.



Subjects

Thirteen men (mean age, 27.8 \pm 4.1 years; mean height, 184.6 \pm 5.5 cm; mean body mass, 99.5 \pm 18.6 kg) were enrolled. They were all interregional to national level discus ($n = 8$) and hammer ($n = 5$) throwers, who had been doing regular strength training and, in particular, bench press exercise for at least 3 years. The study took place at the beginning of the competition

season, so that subjects would be homogenous in terms of training status. The subjects were instructed to avoid strength training the day before laboratory testing and to cancel training on the day itself. In accordance with Lyon Ethics Committee guidelines, the study protocol was explained to the subjects before they gave their written informed consent.

Procedures

Upper-limb force was assessed on a series of bench press movements made with a guided horizontal barbell against increasing loads (7, 15, 24, 34, 44, 54, 64, and 74 kg). The barbell, the mass of which totaled 24 kg including the guidance system, was modified to obtain the lightest (7 and 15 kg) loads; both ends of the barbell were taken off for the 15-kg load, and the barbell as such was replaced by an aluminum tube of the same diameter for the 7-kg load. This protocol allowed each subject to be compared for a given load.

The test session began with a general warm-up involving several sets of bench press exercise at low loads. Subjects lay supine on the bench (Figure 1). The barbell was positioned across their chest at nipple level above the pectoralis major, supported by the lower mechanical stops of the measurement device. At the start of the movement, the shoulders had to stay in contact with the bench. The subjects held the barbell at shoulder width, with an initial elbow angle of 90° between the upper arm and forearm (14,29), as checked with a protractor, and the barbell was marked so as to be held at exactly the same place in all trials. The subjects held their legs crossed above the bench. On a spoken order, the subject applied force as fast as possible to perform an explosive concentric arm extension. The subjects did not have to lower the bar to their chest, just to explode it off the chest as rapidly as possible. The barbell had to stay in the subjects' hands throughout the movement and could not be thrown. Two trials were performed at each load. Each trial was followed by a rest period of at least 3 minutes. The best trial, in terms of force peak as measured by the force plate, was used for analysis.

Measuring System

All lifts were performed by using the same guided horizontal barbell (Multipower Basic; Panatta Sport, Airo, Italy) and allowing only vertical movement. Extra load was added by adding weight plates equally to both ends of the bar.

Variation in the vertical force during the movement was recorded by a Kistler force plate (Kistler type 9281 Kistler Instrumente AG, Winterthur, Switzerland). Analog signals from the force plate were amplified by charge amplifiers (Kistler type 9861A; Kistler Instrumente AG). The force plate was mounted according to the manufacturer's specifications and had been calibrated by the manufacturer; no periodic recalibrating was necessary. The force plate was fixed to the ground with a base provided by the manufacturer. The bench was also fixed onto the force plate. The force signal was linear ($<0.5\%$) over a range of force of 0 to 10 kN, to within $\pm 1\%$. The resonant frequency of the force platform was greater than 200 Hz. The amplifiers were reset to 0 after the subject took his place on the bench. F_{peak} designates the peak force values recorded by the force plate during the movement.

The displacement signal was recorded by a valid and reliable kinematic system (3,24), consisting of 2 infrared photo interrupters, locked in a shuttle that glided on a track bar (Figure 1) and was fixed onto the barbell. The optical encoder was placed facing an optical code strip

that was stuck to the track bar and composed of slots 0.75 mm apart. The optical encoder counted the slots as it passed them and recorded each 0.75-mm displacement as the load was being raised by the subject. Displacement was recorded over a maximum distance of 2,000 mm with a minimum speed of 0.008 m·s⁻¹. The displacement signal was stored on a personal computer (486 DX2, 66 MHz). Customized software calculated the instantaneous velocity and acceleration from successive displacement time-derivatives for each lift. Instantaneous force (F, measured in newtons) was calculated as follows: $F = M(a + g) + F_f$; where M is the moving mass; g is the gravitational acceleration (9.81 m·s⁻²); a is the calculated acceleration (m·s⁻²); and F_f is the friction force determined by a freefall test added to the concentric phase. F was determined by taking into account only the barbell load (F_{peakb}) or the combined mass of the load plus the upper limbs (F_{peakt}), as estimated from Winter's anthropometric tables (38). The index *b* is used here and throughout to signify that upper-limb mass was not taken into account, and the index *t* is used to indicate that it was. The instantaneous power, measured in watts, was calculated as the product of force and velocity at any given time. The calculation is detailed in work published by Bosco et al. (3).

The displacement and force signals were sampled simultaneously (200 Hz) and stored on a personal computer (486 DX2, 66 MHz) by an electronic interface card equipped with a 12-bit counter (type HCTL-2000; Hewlett Packard, Palo Alto, CA) for the kinematic device and a 12-bit A/D converter card (type PC-LPM16; National Instrument France, Le Blanc-Mesnil, France) for the force plate. The signals were digitally filtered with a 12-Hz low-pass Butterworth filter with no phase lag.

Force–Velocity and Power–Velocity Relationships

The relationships between force and velocity and between power and velocity were determined from the kinematic data for each subject. For each load, the peak force and corresponding velocities were recorded (23).

The force–velocity relationships were described by linear regression between the force and the velocity of the movement for each load lift; a nonlinear force–velocity model would not have increased correlation coefficient values consistently. The theoretical maximal isometric force (F₀) and maximal contraction velocity (V₀), corresponding to the force–velocity curve intercepts with the force and velocity axes, respectively, were extrapolated from the curve and annotated as F_{0b} or F_{0t} for force and V_{0b} or V_{0t} for velocity, depending on the mass definition used. For each load, the peak power values and corresponding velocity were recorded (23). The power–velocity relationships were described by a second-order polynomial regression. P_{max} and V_{opt} were extrapolated from the curve and annotated as P_{maxb} or P_{maxt} for power and V_{optb} or V_{optt} for velocity, depending on the mass definition used.

Statistical Analyses

Data are presented as mean ± SD. The statistical significance threshold was set at $P \leq 0.05$. In agreement with statistical norms (19), trial-to-trial reliability was tested on F_{peakt} by assessing the intraclass correlation coefficient (ICC) between the 2 trials recorded with the force plate. The ICC and statistical power were calculated from analysis of variance with repeated measures.

The Pearson product–moment correlation coefficient (*r*) was used to compare F_{peakt} and F_{peakb} and to determine the force–velocity and power–velocity relationships. The Wilcoxon test was used to compare force values per load under the various measurement and calculation conditions and to compare parameters determined on the basis of the force–velocity and power–velocity relationships, including upper-limb inertia or not.

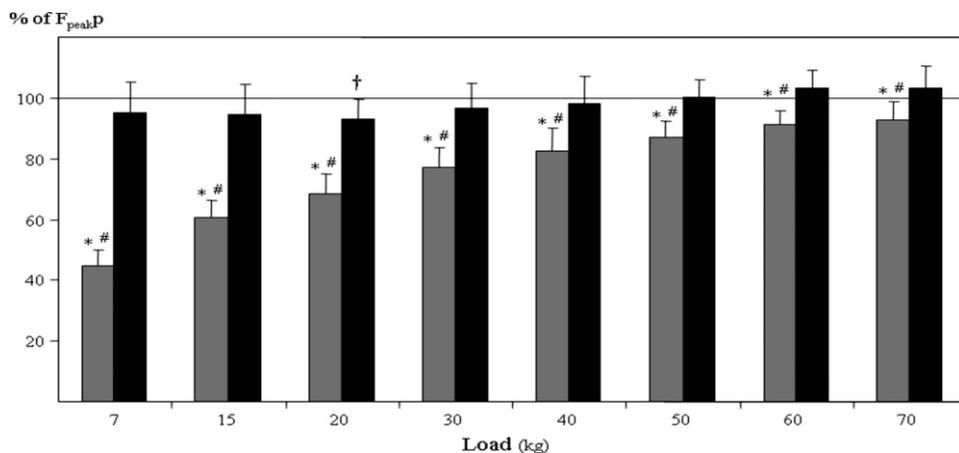


Figure 2. Force peak values taking and not taking upper-limb inertia into account (F_{peakt} in black and F_{peakb} in gray, respectively) related to reference force peak values (F_{peakP}) for each experimental load. * Significantly different from 100% F_{peakP} ($P < 0.0001$). † Significantly different from 100% F_{peakP} ($P < 0.01$). # F_{peakb} significantly different from F_{peakt} ($P < 0.0001$)

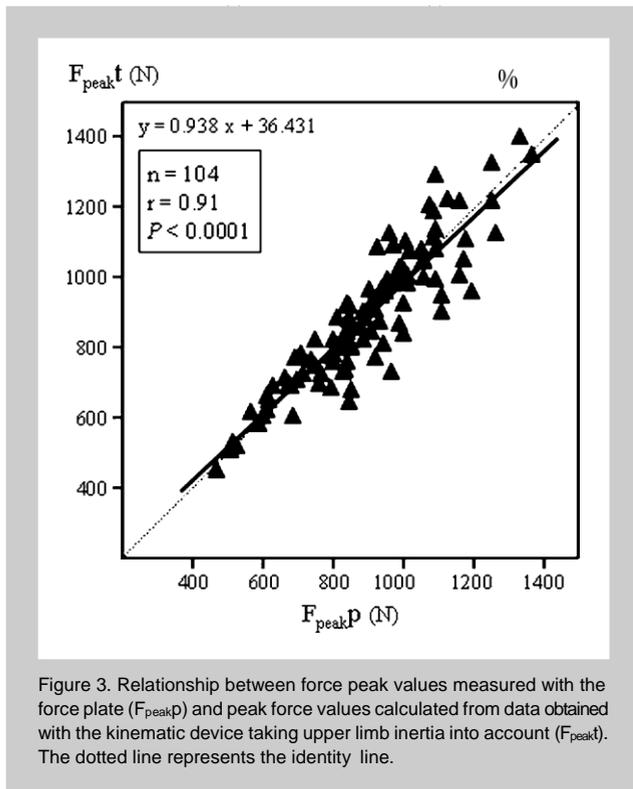
RESULTS

Reliability

The trial-to-trial ICC for F_{peakp} was 0.92, and the statistical power was 97.8%. According to statistical norms (33), the reliability coefficient was very good, with no statistical difference between the 2 trials. This good intertrial reproducibility shows that subjects were accustomed to the bench press and justifies the choice of the best peak-force trial for analysis.

Importance of Inertia

The mean upper-limb mass determined according to Winter (38) was 8.7 ± 1.6 kg. The values of F_{peakb} and F_{peakt} were expressed as a percentage of F_{peakp} (Figure 2). F_{peakp} and F_{peakt} were significantly greater than F_{peakb} , regardless of the load ($P < 0.0001$). The difference between F_{peakp} and F_{peakb} , expressed as a percentage of F_{peakp} , decreased with increasing load, from $55.72 \pm 5.41\%$ to $8.44 \pm 2.10\%$ for 7 kg and 74 kg respectively. F_{peakt} and F_{peakp} did not significantly differ, except at 24 kg ($P < 0.01$). F_{peakt} correlated significantly with F_{peakp} ($r = 0.91$; $P < 0.0001$) (Figure 3).



Force–Velocity and Power–Velocity Relationships

The mean force–velocity and power–velocity relationships are shown in Figure 4. The force–velocity relationships were significantly linear (Figure 4a), regardless of whether upper-limb mass was included in the calculation ($0.75 < r < 0.98$; $P < 0.05$) or not (0.77

$< r < 0.99$; $P < 0.05$). V_{0b} was significantly less than V_{0t} (2.11 ± 0.41 m·s⁻¹ and 3.67 ± 1.06 m·s⁻¹, respectively; $P < 0.01$), and F_{0b} was significantly less than F_{0t} ($1,037.4 \pm 206.6$ N and $1,100.2 \pm 200.1$ N, respectively; $P < 0.01$).

The power–velocity relationships significantly matched a second-order function (Figure 4b), regardless of whether upper-limb mass was included in the calculation ($0.88 < r < 0.99$; $P < 0.05$) or not ($0.96 < r < 0.99$; $P < 0.05$). P_{maxb} was significantly less than P_{maxt} ($1,077.8 \pm 291.2$ W and $1,598.9 \pm 435.7$ W, respectively; $P < 0.01$). Likewise, V_{optb} was significantly less than V_{optt} (1.95 ± 0.21 m·s⁻¹ and 3.04 ± 0.53 m·s⁻¹, respectively; $P < 0.01$).

DISCUSSION

This study shows the importance of taking upper-limb inertia into account if force and power production during all-out bench press exercise is to be evaluated accurately with a kinematic device. When upper-limb mass was ignored, the force calculated with the kinematic device, regardless of the load, was significantly less than that measured with the force plate (Figure 2). This underestimation was greater for lighter loads because the relative contribution of the upper-limb mass to the total inertia decreased as the lifted load increased, from $53.73 \pm 4.78\%$ to $10.38 \pm 1.74\%$ at 7 kg and 74 kg respectively. V_0 , F_0 , P_{max} , and V_{opt} were significantly underestimated, by 40.9%, 5.9%, 32.1%, and 34.9% respectively, when upper-limb inertia was not taken into account.

The percentage error was particularly great in the case of maximal power and velocity parameters values (i.e., V_0 and V_{opt}) because maximal power is obtained for light loads (i.e., high velocities). For the lightest loads, calculated peak force values were underestimated by 56% and 41% for 7 and 15 kg, respectively (Figure 2), when total inertia was not taken into account. These findings support those of Rahmani et al. (23) and Winter et al. (39), who found percentage errors on force values varying from 6% to 45%, depending on the mass and velocity conditions, when total inertia was not taken into account. Failure to consider upper-limb inertia makes it difficult to compare maximal power and optimal velocity between subjects or populations differing in upper-limb mass. Moreover, the load corresponding to maximal power production varied, from a mean of 36 kg when upper-limb inertia was ignored to a mean 15 kg when it was taken into account. This finding has practical consequences in the context of training, particularly for training programs using P_{max} loading to enhance maximal power. The results also showed that the error on F_0 , though significant, was weak. It may be concluded that taking or not taking upper-limb inertia into account during all-out bench press exercise is of particular importance for determining maximal power and velocity, but of minor interest for determining maximal force.

When upper-limb mass was taken into account, there was no significant difference in force values as measured with the kinematic device or the force plate, except in the case of a 24-kg load, and no significant difference between kinematic and force plate results emerged when all loads were analyzed together without distinction. Moreover, F_{peakp} and F_{peakt} were highly correlated, with a regression slope nearly coinciding with the identity line (Figure 3). F_{peakt} tended to be less than F_{peakp} for loads less than 54 kg but greater for greater loads (Figure 2).

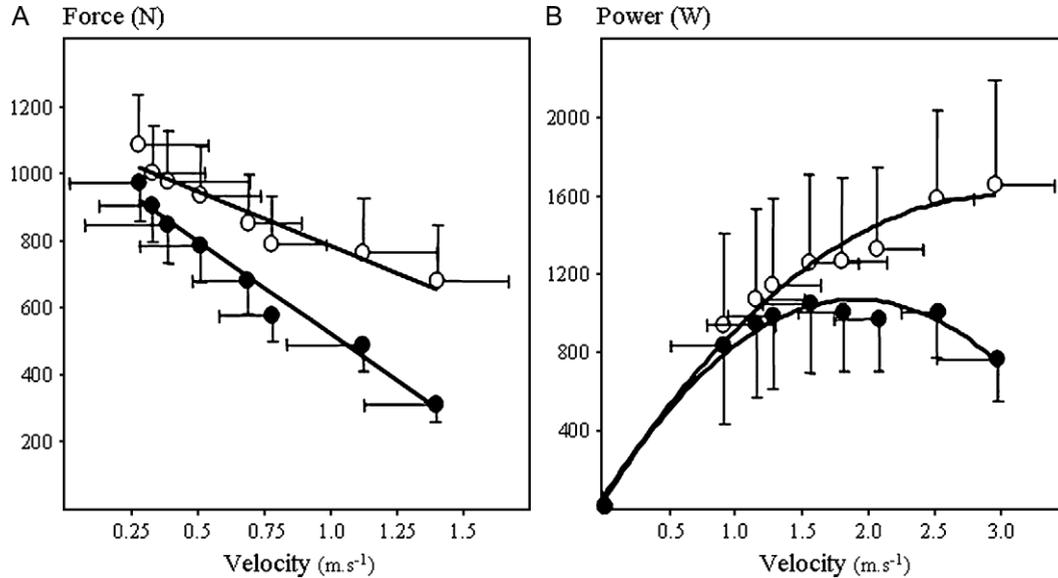


Figure 4. Mean force–velocity (A) and power–velocity (B) relationships taking (open symbols) or not taking (filled symbols) upper-limb mass into account.

This finding probably indicates that the upper-limb mass estimated from the anthropometric tables did not reflect the true inertia. The bench press exercise is a multiple-joint movement involving 2 joints (i.e., the elbow and shoulder); the muscular groups involved come into play progressively, so that inertia may vary during the movement. Complementary studies using a multiple-segmental system to model the upper limbs, including upper-limb inertia, will be necessary to confirm this hypothesis.

Figure 4a,b shows how the shapes of the force–velocity and power–velocity curves are affected when upper-limb inertia is taken into account. These shapes were close to those obtained by Rahmani et al. (25) and Taylor et al. (28). In those studies, maximal power could not be extrapolated accurately from the polynomial regression equation because P_{max} lay outside the experimental points, in contrast to the current study. Reducing the mass of the original barbell to 7 and 15 kg enabled a velocity great enough to allow the apex of the power–velocity relationship to be achieved and P_{max} to be obtained, in contrast to the design by Rahmani et al. (23,25). This raises the main methodological problem encountered in determining maximal power during squat or bench press exercises using a guided barbell. It could be hypothesized that bench throw exercises are more suited to evaluate upper-limb muscular characteristics than bench press exercises are. Newton et al. (21) showed that peak concentric velocities were

significantly greater, by 27 %, during bench throw than during concentric bench press. Further studies are needed to test this hypothesis, although devices enabling bench throw over a wide load range under safe conditions for the athletes are scarce.

PRACTICAL APPLICATIONS

This study confirmed the importance of taking the total inertia of the moving system into account to analyze force–velocity and power–velocity relationships accurately during bench press by using a kinematic device. It further highlights the importance of using light loads to enhance the range of velocities in assessing upper-limb muscular parameters to determine P_{max} accurately. P_{max} often correlates with performance in explosive events; precise determination of P_{max} would allow interindividual performance variations between throwers to be analyzed. It has a practical application in training; ignoring inertia prevents accurate determination of the load at which an athlete or a practitioner should work to improve his or her power. This protocol allows muscular characteristics to be determined with precision in laboratory and field conditions by using a simple and relatively inexpensive kinematic device.

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