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A virtual model of the bench press exercise

Abderrahmane Rahmani [a,*], Olivier Rambaud [b], Muriel Bourdin [b], Jean-Pierre Mariot [a]

[a] *Laboratoire Motricité, Interactions, Performance, EA 4334, Université du Maine, Olivier Messiaen Avenue, 72085 Le Mans Cedex 09, France*
[b] *Université de Lyon, Lyon, INRETS, LBMC UMRT_9406, Université Lyon 1, BP12, F-69921 Oullins Cedex, France*

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ABSTRACT

The objective of this study was to design and validate a three degrees of freedom model in the sagittal plane for the bench press exercise. The mechanical model was based on rigid segments connected by revolute and prismatic pairs, which enabled a kinematic approach and global force estimation. The method requires only three simple measurements: (i) horizontal position of the hand (x_0); (ii) vertical displacement of the barbell (Z) and (iii) elbow angle (θ). Eight adult male throwers performed maximal concentric bench press exercises against different masses. The kinematic results showed that the vertical displacement of each segment and the global centre of mass followed the vertical displacement of the lifted mass. Consequently, the vertical velocity and acceleration of the combined centre of mass and the lifted mass were identical. Finally, for each lifted mass, there were no practical differences between forces calculated from the bench press model and those simultaneously measured with a force platform. The error was lower than 2.5%. The validity of the mechanical method was also highlighted by a standard error of the estimate (SEE) ranging from 2.0 to 6.6 N in absolute terms, a coefficient of variation (CV) $\leqslant 0.8\%$, and a correlation between the two scores $\geqslant 0.99$ for all the lifts ($p < 0.001$). The method described here, which is based on three simple parameters, allows accurate evaluation of the force developed by the upper limb muscles during bench press exercises in both field and laboratory conditions.

1. Introduction

Force, velocity and power are the muscular characteristics generally associated with performance in explosive events. These parameters can be determined by the use of a force platform, but this is an expensive tool that needs to be used carefully in laboratory conditions. Bosco et al. (1995) developed a kinematic device that can be applied to any guided apparatus using gravitational loads as external resistance. The force produced during weightlifting can be derived from a precise measurement of the vertical displacement of a lifted mass.

The principle of this device is based on the hypothesis that the acceleration of a lifted mass represents acceleration of the centre of mass of the entire moving system (i.e., the lifted mass along with the limb segments involved in the movement) during the movement. Support for the hypothesis has been provided by studies of the squat exercise (Rahmani et al., 2000). Those authors showed that velocity–, force– and power–time curves obtained with the kinematic device and those measured simultaneously from a force platform were identical during the pushing phase. This result was expected since, in a first approximation, the centre of mass of the subject is located above the lower limbs, indicating that the distance between the centre of mass of the subject and the centre of mass of the lifted mass does not change during the movement. Consequently, acceleration of the subject and the lifted mass is due to the acceleration of the lower limbs. Recently, Rambaud et al. (2008) showed no difference between the forces derived from the kinematic device compared to those measured simultaneously with a force platform, and calculated the force produced during the bench press exercise by adding the total mass of the arm and forearm segments, but neglecting the acceleration applied to these segments. In contrast to the squat exercise, the global centre of mass (i.e., the upper limbs and the lifted mass) located between the shoulder and the lifted mass is moved during the arm and forearm rotations during the bench press exercise. It is important to know if the acceleration of the barbell is identical with the acceleration of the centre of mass of the system constituted by the upper limbs and the lifted mass. This can be done by adding a multi-segmental system of the upper limbs to the kinematic device proposed by Bosco et al. (1995).

The present study had two objectives. Firstly, a multi-body model was designed to characterize the kinematic parameters (vertical displacement, velocity and acceleration) of the combined centre of mass of the upper limbs and the lifted mass. This allows determination of whether the characteristics of the bench press exercise measured with a kinematic device truly reflect the action

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[*] Corresponding author. Tel.: +33 243 832 635; fax: +33 243 833 662.
E-mail address: arahm@univ-lemans.fr (A. Rahmani).

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of the subject measured simultaneously with a force platform. Secondly, this study aimed at validating the proposed model by comparing the forces calculated from the model with those measured simultaneously with the force platform. This was done by analysing the mean forces on the whole force–time curves during the entire bench press exercise.

2. Methods

2.1. Subjects

Eight adult male volunteers accustomed to developing maximum effort during the dynamic bench press exercise (mean (SD): age 27.4 (5.8) years; height 184.7 (4.1) cm; body mass 101.0 (14.2) kg) participated in the study. The testing session was part of a standard evaluation procedure. The subjects gave written informed consent to take part in this study, which was approved by the Lyon Ethics Committee.

2.2. Study protocol

Dynamic bench press exercises were done with a guided horizontal barbell (Multipower Basic, Panatta Sport, Apiro, Italy), allowing only vertical movement (Fig. 1). The test session began with a general warm-up involving several sets of bench press exercises at submaximal loads. Subjects were then instructed to lie on the bench so that the bar crossed their chest at nipple level. At the start of the movement, the shoulders were to stay in contact with the bench, and the upper segments were placed to obtain an elbow angle of 90°, checked with a goniometer (model SEEB 502, accuracy 1°, Sfernice, Nice, France). The subject's legs were crossed above the bench to avoid any utilization of the lower limbs. Once the position was adopted, mechanical stops in the guided barbell were positioned below the bar, and marks were placed on the barbell so that the appropriate angle was ensured in all trials.

The upper limb force was assessed for a series of bench press movements made with the horizontal barbell against increasing mass (24, 34, 44, 54, 64 and 74 kg). The mass of the barbell including the guiding system was 24 kg. Upon a verbal command, the subject applied force as fast as possible to perform an explosive concentric arm extension. The subjects were not required to lower the bar to the chest, just to explode it off the chest as rapidly as possible. The barbell had to remain in their hands throughout the movement, so as to maintain the same conditions as during the training program. Two trials were performed at each load, and each trial was followed by a rest period of at least 3 min. The statistical analysis used data for the most rapid trial, defined as the trial in which the mass was lifted in the shortest time.

2.3. Sensors

The kinematic device, which consisted of two infrared photo-interrupters locked in a shuttle that glided on a track bar fixed on the barbell (Bosco et al., 1995), faced an optical code strip, composed of slots placed 0.75 mm apart, fastened on the track bar. The optical encoder counted the slots as it passed them, and recorded each 0.75 mm vertical displacement when a mass was raised by the subject. Displacement was recorded over a maximum distance of 2 m with a minimum speed of 0.008 m s^{-1}. The displacement signal was stored in a computer via an electronic interface card equipped with a 12-bit counter (Hewlett Packard, type HCTL-2000, Palo Alto, California, USA), and digitally filtered with a 12 Hz low-pass Butterworth filter with 0 phase lag. The displacement of the barbell and the elbow angle θ were both smoothed with a seven-degree polynomial function.

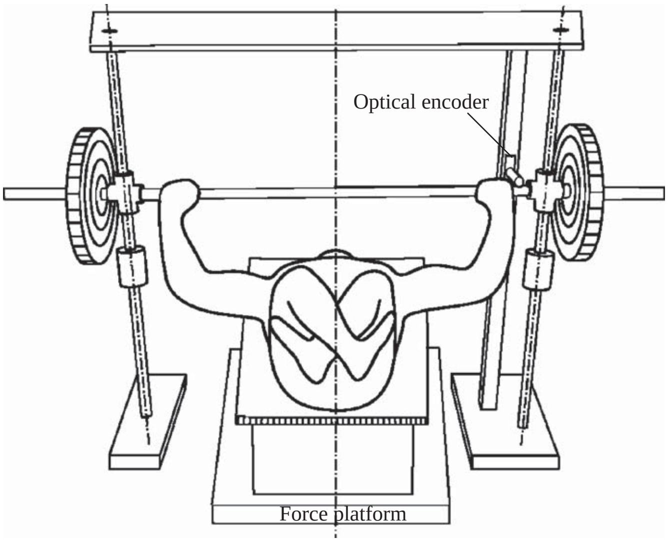

Fig. 1. A picture of the guided horizontal barbell used during the bench press exercise.

Variation in vertical force during the movement was recorded simultaneously with a Kistler force plate (Kistler type 9281, Kistler Instrumente AG, Winterthur, Switzerland). Analogue signals from the force plate were amplified by charge amplifiers (Kistler type 9861A, Kistler Instrumente AG, Winterthur, Switzerland). The force plate had been calibrated by the manufacturer and was mounted according to the manufacturer's specifications; no recalibration was necessary. The bench was fastened to the force plate and was isolated from the ground. The force signal was linear ($<0.5\%$) over a force range of 0–10 kN, with a degree of accuracy close to $\pm 1\%$. The resonant frequency of the force platform was >200 Hz. The amplifiers were reset to zero after the subject took his place on the bench.

2.4. Mechanical model

2.4.1. Description of the model

Since the bench press exercises are realised by accustomed athletes with a guided horizontal barbell, actions of the two upper limbs can be assumed to be symmetrical. Consequently, for the mechanical bench press model, half of the bar was considered and the model had three degree of freedom. Two revolute joints were introduced to model the shoulder and elbow rotations, and the vertical shoulder displacement (Z_S) was represented by introducing a prismatic joint (Fig. 2a). The bench press movement was considered only in the vertical plane. The position of the subject's hands was noted (x_0, Z). The coordinate x_0 represents the horizontal position of the hand, which was constant because the movement was performed under a vertically guided barbell. Z is the vertical displacement of the barbell and Z_0 is the vertical position of the hand at rest relative to the horizontal axis. The absolute angle of the upper arm (θ_a) and forearm (θ_a+θ_f) were expressed relative to the horizontal axis. θ_f was calculated from the angle measured between the upper arm and the forearm as $\theta_f = 180° - \theta$, where the anatomic angle of the elbow θ was measured by goniometry. One part of the goniometer was attached to the subject's upper arm, and the other to the forearm. The axis of the goniometer was aligned with the joint axis (i.e., the elbow). Z_S is the vertical displacement of the shoulder, L_a is the length of the upper arm and L_f is the length of the forearm, both estimated from Winter's table (Winter, 2005).

2.4.2. Inverse kinematic model

An inverse kinematic model (Fig. 2a) was used to calculate the joint coordinates θ_a and Z_S derived from the vertical displacement Z and the elbow angle θ_f.

The horizontal position x_0 of the hand can be written as

$$x_0 = L_a \cos\theta_a + L_f \cos(\theta_a + \theta_f) \tag{1}$$

The absolute angle of the arm θ_a (in radians) is derived from Eq. (1):

$$\theta_a = tan^{-1}\left(\frac{Bx_0 + A\sqrt{C - x_0^2}}{Ax_0 + B\sqrt{C - x_0^2}}\right) \tag{2}$$

where $A = L_a + L_f \cos\theta_f$, $B = -L_f \sin\theta_f$ and $C = A^2 + B^2$.

The method is fully described in Appendix A.

The vertical displacement of the shoulder Z_S is derived from the vertical position of the hand:

$$Z + Z_0 - Z_S = L_a \sin\theta_a + L_f \sin(\theta_a + \theta_f) \tag{3}$$

To express Z_S, it is necessary to calculate the initial vertical position of the hand at rest, Z_0, relative to the horizontal axis. Z_0 was determined geometrically (Fig. 2b). In the triangle *SAW*, Pythagoras' theorem leads to

$$x_0^2 + Z_0^2 = SW^2 \tag{4}$$

In Fig. 2b, the *SW* side of the triangle can be expressed as

$$SW^2 = L_a^2 + L_f^2 - 2L_aL_f \cos\theta_0 \tag{5}$$

From Eqs. (3) and (4), Z_0 can be deduced as

$$Z_0 = \sqrt{L_a^2 + L_f^2 - 2L_aL_f \cos\theta_0 - x_0^2} \tag{6}$$

Then Z_S is equal to (Appendix A)

$$Z_S = Z + Z_0 - \sqrt{C - x_0^2} \tag{7}$$

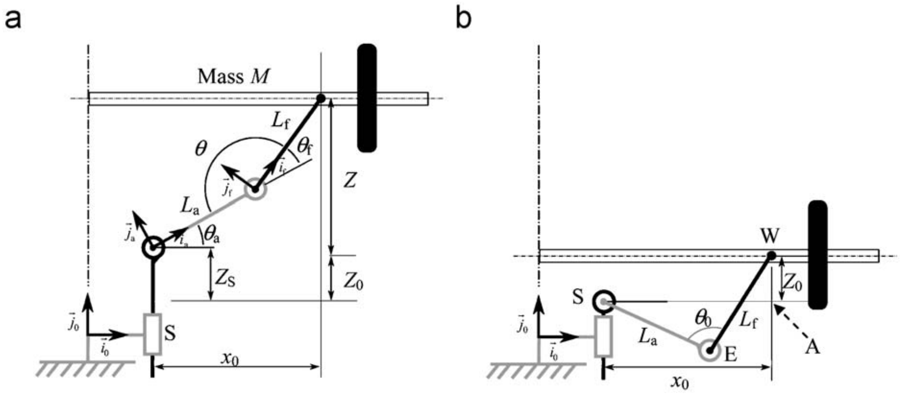

Fig. 2. (a) Mechanical model of the upper limb during the bench press exercise with 3 limb segments linked by 2 revolute joints and a prismatic joint: x_0, horizontal position of the wrist; Z_0, initial vertical position of the wrist relative to the horizontal axis; Z, vertical displacement of the lifted mass; L_a, upper arm length; L_f, forearm length; θ: elbow angle; θ_a, absolute upper arm angle; θ_f, forearm angle relative to the arm position. (b) Initial position of the subject: S, shoulder; E, elbow; W, wrist; A, orthogonal projection of the wrist on the horizontal axis; θ_0, initial elbow angle.

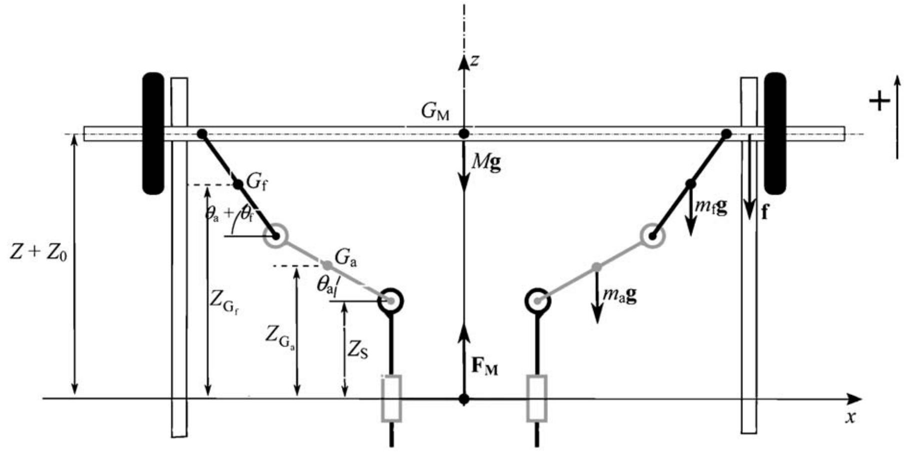

Fig. 3. Diagram of (i) the external forces applied to the limbs and barbell system in one hand and (ii) the vertical position of centre of mass of the upper arm (Z_{G_a}) and forearm (Z_{G_f}) during the bench press exercise. F_M, force produced by the subject; f, friction forces; $m_a g$, $m_f g$ and Mg, weights of the upper arm, forearm and lifted mass, respectively; θ_a, absolute angle relative to the horizontal axis; θ_a+θ_f, absolute angle between the upper arm and the forearm.

2.5. *Acceleration of the combined centre of mass*

In the present study, the human body is considered as two separate mechanical systems. System S_1 contains the lifted mass (M), the upper limbs (upper arms and forearms), and the shoulders (the mass of the shoulders is neglected in the present study) (Fig. 3). System S_2 is composed of the trunk, the head and the lower limbs at rest, and is assumed to remain fixed during the bench press exercise. The arm and forearm masses (m_a and m_f, respectively) were estimated from Winter's table (Winter, 2005). The vertical position Z_G of the combined centre of mass of the lifted mass, upper arms, forearms and hands is

$$Z_G = \frac{M(Z+Z_0) + 2m_a Z_{G_a} + 2m_f Z_{G_f}}{M + 2m_a + 2m_f} \tag{8}$$

where Z_{G_a} and Z_{G_f} are the vertical displacement of the centre of mass of the upper arm and forearm, respectively. Z_G was twice derivated to calculate the acceleration $\ddot{Z}_G$ of the combined centre of mass.

2.6. *Force calculations*

The force produced at the shoulder during the bench press exercise was calculated with two methods (F_K and F_M). F_K was calculated as (Rambaud et al., 2008)

$$F_K = (M + m_a + m_f)(a + g) + F_f \tag{9}$$

where M is the lifted mass, g is the gravitational acceleration (9.81 ms^{-2}), a is the calculated acceleration (in ms^{-2}) derived from the vertical displacement and F_f is the friction force determined by a freefall test added to the concentric phase.

F_M was determined from the mechanical model and can be expressed as

$$F_M = M\ddot{Z} + 2m_a\ddot{Z}_{G_a} + 2m_f\ddot{Z}_{G_f} + (M + 2m_a + 2m_f)g + F_f \tag{10}$$

where $\ddot{Z}$, $\ddot{Z}_{G_a}$ and $\ddot{Z}_{G_f}$ are the acceleration of the lifted mass, the upper arm and the forearm segments, respectively, g is the acceleration of gravity (9.81 ms^{-2}) and F_f is the friction force (9.6 ± 0.9 N) determined by a freefall test, were added during the concentric phase. The values m_a and m_f were multiplied by 2 to take the two upper limbs into account, assuming that the movement was symmetric. $\ddot{Z}$, $\ddot{Z}_{G_a}$ and $\ddot{Z}_{G_f}$ were derived from the vertical displacement Z of the lifted mass, and the vertical displacement of the upper arm and forearm centre of mass, respectively. The method is fully described in Appendix B (see supporting material).

2.7. *Statistical analysis*

The results are presented as mean ± standard deviation. The validity of the mechanical model was established by comparing forces calculated from the bench press model to those simultaneously measured with a force platform. Differences between the 2 methods are expressed as standard error of the estimate (SEE) and the coefficient of variation (CV). The Pearson product–moment correlation coefficient (r) was used to calculate the correlations between the 2 scores. For each lift, mean differences were used to compare mean force values per load under the various measurement and calculation conditions (i.e., platform F_P, kinematic device considering only the upper limbs and the lifted mass F_K, and kinematic device associated to the mechanical model F_M). Mean differences were determined and expressed with 95% confidence limits to establish the precision of the estimate. The practical significance of differences criterion (force platform) and practical measures (model) was based on the smallest worthwhile difference with a small standardized (Cohen) effect size (>0.2), derived by dividing the mean difference by the between-subject standard deviation (Drinkwater et al., 2007; Vincent, 1995). Chances of a substantial true difference were interpreted

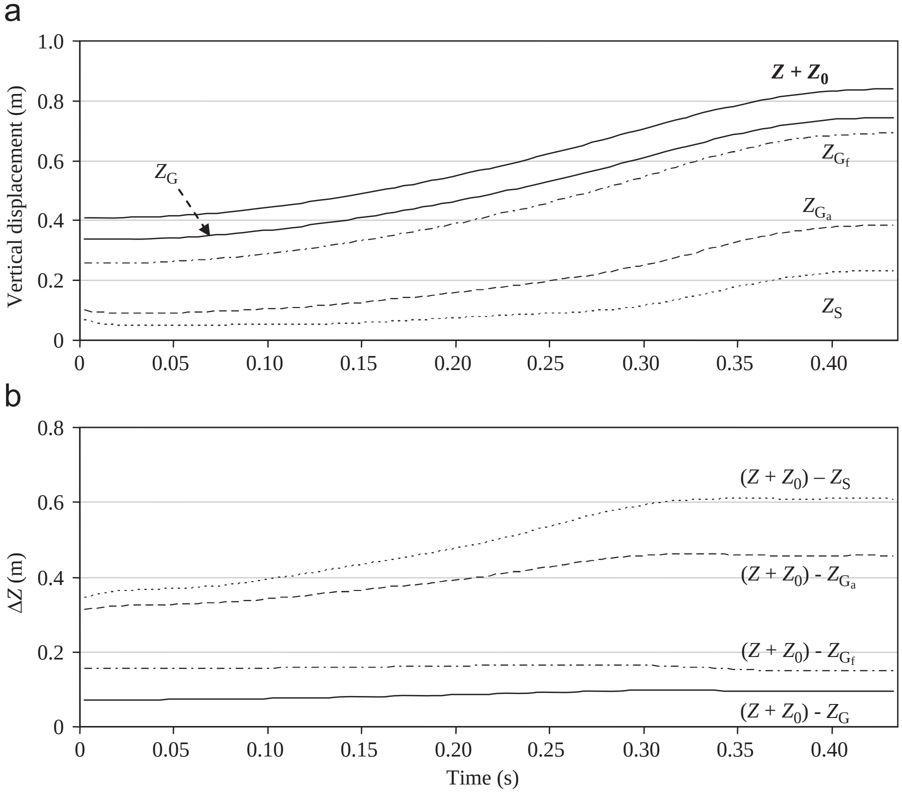

Fig. 4. Example of (a) vertical displacement–time curves for the lifted mass (Z+Z_0), the global centre of mass Z_G, the forearm centre of mass Z_{G_f}, the upper arm centre of mass Z_{G_a}, and the shoulder (Z_S) during a bench press exercise with a weight of 44 kg. (b) Differences between Z+Z_0 and Z_G, Z_{G_f}, Z_{G_a} and Z_S.

Table 1
Mean values ± SD of the difference between Z and Z_G on one hand, and Z_{G_f} on the other hand.

Mass (kg)	Z–Z_G (m)	Z–Z_{G_2} (m)
24	0.081 ± 0.013	0.152 ± 0.018
34	0.063 ± 0.011	0.0158 ± 0.006
44	0.056 ± 0.014	0.0158 ± 0.005
54	0.044 ± 0.007	0.0158 ± 0.005
64	0.036 ± 0.005	0.0158 ± 0.007
74	0.033 ± 0.006	0.0158 ± 0.006

qualitatively as follows: $<$1%, almost certainly not; $<$5%, very unlikely; $<$25%, unlikely; 25–75%, possible; $>$75%, likely; $>$95%, very likely; $>$99% almost certain (Petersenn et al., 2004; Liow and Hopkins, 2003). The level of statistical significance was set at $p<0.05$.

3. Results

3.1. Kinematic parameters

The vertical displacement–time curves for the lifted mass Z, the centre of mass of the total system Z_G, the centre of mass of the forearm Z_{G_f} and the upper arm Z_{G_a} and the shoulder Z_S was identical but not equal to Z (Fig. 4a). Fig. 4b presents the difference between the vertical displacement Z+Z_0 and Z_G, Z_{G_f}, Z_{G_a} and Z_S. Differences between Z and Z_G, and between Z and Z_{G_f} are given in Table 1. The difference between Z_G and Z was constant for a given lifted mass throughout the bench press exercise. The greater the lifted mass, the smaller the difference between Z_G and Z, ranging from 0.08 ± 0.01 m (for 24 kg) to 0.033 ± 0.006 m (for 74 kg). Consequently, the vertical velocity and acceleration (Fig. 5) of the combined centre of mass and the lifted mass were identical during the bench press exercise. The difference between Z and Z_{G_f} was constant (0.16 ± 0.01 m) for the whole displacement–time curve, whatever the subject or the lifted mass. Differences between Z and both Z_S and Z_{G_a} followed the same profile whatever the subject or the lifted mass, and increased progressively during 64.6 ± 0.9% of the total displacement, and then was constant until the end of the movement, at that time there was a difference of 0.58 ± 0.07 m for Z_S and 0.44 ± 0.06 m f or Z_{G_a}.

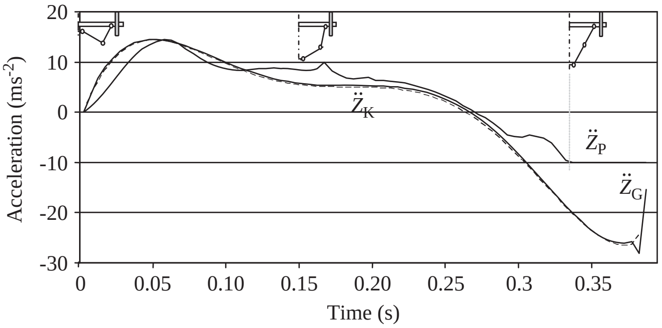

Fig. 5. Typical acceleration–time curves obtained from the kinematic device ($\ddot{Z}_K$, $\ddot{Z}_G$) and the force platform ($\ddot{Z}_P$).

3.2. Validity of the proposed model

A typical example of the acceleration–time curve obtained from the force platform is presented with the acceleration of the lifted mass and the centre of mass of the model in Fig. 5. The acceleration determined by the model and the lifted mass followed the acceleration measured simultaneously with the

Table 2
Mean values ± SD of F_K, F_M and F_P, and characteristics of correlations and regressions between F_M and F_P.

Mass (kg)	F_K (N)	F_M (N)	F_P (N)	Pearson correlation coefficient (r)	Slope of the linear regression line[a]	y intercept of the linear regression line[b]
24	620 ± 95	619 ± 97	621 ± 99	0.99***	0.98	9.79
34	698 ± 96	697 ± 95	694 ± 95	0.99***	1.003	0.32
44	804 ± 86	804 ± 85	805 ± 85	0.99***	0.998	−0.04
54	827 ± 105	829 ± 109	829 ± 108	0.99***	1.010	−8.58
64	875 ± 101	875 ± 103	875 ± 102	1.00***	1.01	−6.93
74	943 ± 93	943 ± 91	942 ± 91	0.99***	0.99	1.70
All				0.99***	1.00	−2.33

[a] Not significantly different from unity.
[b] Not significantly different from 0.
*** $p < 0.001$.

Table 3
Standard error of the estimate (SEE, in N), coefficient of variation (CV in %) and practical significance of difference between mean forces predicted with the model and those measured with the force platform.

Mass (kg)	Standard error of estimate (SEE)			Coefficient of variation (CV)			Practical significance of difference (%)[b]
	Absolute (N)	Lower[a]	Upper[a]	%	Lower[a]	Upper[a]	
24	3.9	2.6	8.8	0.6	0.4	1.4	2.5, very unlikely
34	5.3	3.7	10.1	0.7	0.5	1.4	2.3, very unlikely
44	6.6	4.6	12.7	0.8	0.6	1.6	1.6, very unlikely
54	4.8	3.3	9.2	0.6	0.4	1.2	0.6, almost certainly not
64	2.0	1.4	3.8	0.2	0.2	0.4	0.7, almost certainly not
74	4.8	3.3	9.2	0.5	0.4	1.0	0.9, almost certainly not
All	4.0	2.6	8.8	0.6	0.5	0.8	2.5, very unlikely

[a] Lower and upper refer to lower and upper confidence limits for the mean estimate of the SEE and CV, respectively.
[b] Thresholds for assigning qualitative terms to chances of substantial effects were as follolws: <1%, almost certainly not; <5%, very unlikely; <25%, unlikely; <50%, possibly not; >50% possibly; >75%, likely; >95%, very likely; >99% almost certain.

force platform, except at the end of the movement. Table 2 gives the mean and standard deviation of the average values of F_K, F_M and F_P for each lifted mass. F_M was significantly correlated to F_P ($r = 0.99$, $p < 0.001$), with a slope equal to unity (slope = 1.003) considering all the measurements and also for each lifted mass (Table 2). The SEE between F_P and F_M for all lifts, expressed as a CV, was $\leqslant 0.6\%$ and ranged from 2.0 to 6.6 N in absolute terms (Table 3). The SEE between F_P and F_K for all lifts, expressed as a CV, was $\leqslant 4\%$ and ranged from 4.1 to 24.9 N in absolute terms. Whatever the lifted mass, we estimated that there is almost or very unlikely no difference between the measures realised by the model and the force platform. The practical difference between the 2 scores was less than 2.5% considering all the measurements and also for each lifted mass.

4. Discussion

4.1. Kinematic parameters

The results showed that the difference between Z and Z_G was constant for a given lifted mass, giving the same velocity and acceleration. This is due to the position of the centre of mass of the moving system, which is always located close to the most important mass (i.e., the lifted mass). In addition, the heavier the lifted mass, the shorter the distance between the centre of mass of the system and that of the lifted mass (Table 1). For masses of less than 24 kg, the centres of mass are further apart, but keep a similar vertical displacement. The results showed also that the vertical displacement of the forearm centre of mass Z_{G_f} is identical with that of the lifted mass. The constant difference between the two curves throughout the movement, whatever the lifted mass or the subject, indicated that the elbow extension, realised mainly by the triceps brachii at the end of the movement, is too small to influence the centre of mass displacement. The movement of the forearm can then be considered as essentially a translation movement. Finally, the major part of the bench press exercise is due to the arm rotation, realised by the pectoralis major and the anterior deltoid. This is illustrated by the displacement of the arm and shoulder (Z_{G_a} and Z_S, respectively). Despite a similar displacement with the lifted mass, the difference between Z and both Z_{G_a} and Z_S increased progressively during the first 65% of the total movement, describing the removal of the lifted mass with both arm and shoulder. The end of the movement corresponds to the alignment of the upper arms with the forearms, and at this time the difference between Z and both Z_{G_a} and Z_S was constant. This result was obtained for all subjects, whatever the lifted mass. This is explained by the type of bench press used in this study, in which the subject had to keep the barbell in his hands throughout the movement. Even if it takes a longer time to lift a greater mass, the amplitude of the movement is identical whatever the lifted mass (i.e., elbow angle of 90–180°).

Finally, the kinematic results showed that the acceleration calculated from the model is identical with that of the lifted mass (Fig. 5). These accelerations followed that measured directly from the force platform, as it was during the squat exercise (Rahmani et al., 2000). The difference at the end of the measurement was due to the software used. The displacement–time signals recorded during the bench press exercise were smoothed with a seven-degrees polynomial function. Consequently, the acceleration–time signal followed a five-degrees polynomial function. Nevertheless, this part of the movement is out of the pushing phase, and corresponded to the end of the vertical displacement, when the upper limbs were tensed and followed the lifted mass.

4.2. Validity of the model

The biomechanical bench press model described here is a valid means to estimate the force F_M produced during the bench press exercise; indeed, F_M was not significantly different from F_P. The practical differences between the 2 scores are less than 2.5% considering all the measurements and also for each lifted mass. The validity of the model is also supported by a low CV of 0.2–0.8% and high r values of 0.99 ($p < 0.001$) for each lifted mass.

Comparisons of F_M and F_K did not show any significant difference, indicating that acceleration of the upper arm and forearm can be neglected for a global evaluation of the force produced during the bench press exercise when a kinematic device is used. Nevertheless, force calculation should take the mass of the upper limbs into account. This is in accordance with results obtained during bench press (Rambaud et al., 2008) and squat exercises (Rahmani et al., 2001). Nevertheless, an inverse dynamical model is easily constructed using the present model together with the experimental results, allowing the determination of joint forces and torques. For this, determination of the acceleration of the upper arm and forearm is also necessary. This model presents practical applications in several fields. The model could easily be utilized by sport scientists to identify relative importance of each muscle group in upper limb extension. It will help coaches and athletes to individualize training and monitor the progress. It could also improve understanding of upper limb injury occurrence and permit to assess actual rehabilitation program efficiency. An additional application of the present model concerns the movement analysis of the upper limb during working task. The model determines the characteristics of muscles under conditions close to those of day-to-day activities since upper limb extension is a basic movement of the life. It could help ergonomist to adapt movement in order to limit upper limb injuries. Lastly, application of the model could inform clinicians about upper limb orthesis efficiency.

5. Conclusion

The mechanical model described here has been shown to be a validated method that can be used to evaluate the force produced during the bench press exercise, which is a common training exercise for many types of athlete, with a precision similar to that obtained with a force platform. This method is convenient for field use, because the computations require only three simple measurements: (i) horizontal position of the hand (x_0); (ii) vertical displacement of the barbell (Z) and (iii) elbow angle (θ). Lastly, further studies are needed to determine the joint forces and torques.

Conflict of interest statement

All authors disclose any financial and personal relationships with other people or organisations that could inappropriately influence the work presented in this article.

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Appendix A. Supporting material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jbiomech.2009.04.036.

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