



HAL
open science

A Simple Method for Measuring Force, Velocity, Power and Force-Velocity Profile of Upper Limbs

Abderrahmane Rahmani, Baptiste Morel, Pierre Samozino

► **To cite this version:**

Abderrahmane Rahmani, Baptiste Morel, Pierre Samozino. A Simple Method for Measuring Force, Velocity, Power and Force-Velocity Profile of Upper Limbs. Biomechanics of Training and Testing Innovative Concepts and Simple Field Methods, Springer International Publishing, pp.139-162, 2018, 978-3-319-05632-6. 10.1007/978-3-319-05633-3_7. hal-02357912

HAL Id: hal-02357912

<https://hal.science/hal-02357912>

Submitted on 9 Dec 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Chapter 7

Simple Method for Measuring Force, Velocity, Power and Force-Velocity profile of Upper Limbs

Abderrahmane Rahmani¹, Baptiste Morel¹, Pierre Samozino²

¹*Le Mans University, Laboratory “Movement, Interactions, Performance” (EA 8 4334), Faculty of Sciences and Technologies, Department of Sport Sciences, Le Mans, France.*

²*University Savoie Mont Blanc, Laboratoire Interuniversitaire de Biologie de la Motricité, EA 7424, F-73000 Chambéry, France*

Address for correspondence: Laboratoire “Motricité, Interactions, Performance” EA 4334, Université du Maine, Avenue Olivier Messiaen, 72085 Le Mans cedex 9 (abdel.rahmani@univ-lemans.fr)

ABSTRACT

Upper limb abilities can be assessed from different kinds of exercises (e.g., cranking, push-up, and medicine ball put test). Since the bench press is a very common exercise used in training routines by most athletes in many sports, its interest in the scientific literature raised in the past two decades. As presented in previous chapters during jumping or cycling, from several bench presses performed against different loads, coaches and athletes can simply and accurately define their upper limb force-velocity (F-v) profile. They can estimate their theoretical maximal force (F_0), velocity (V_0) and power (P_{max}). The aim of this chapter is to present the important points that must be taken into account to optimize the use of the bench press as a routine testing.

In a first part, this chapter will focus on the importance of taking into consideration all the mechanical inertia involved in the bench press exercise. Not considering the upper limb mass in the calculation of the force produced during the exercise implies an underestimation in the F-v profile that can reach 30% for P_{max} . This could conduct to incorrect choices in the optimal load during training and thus limit the performance improvement.

In the second part of this chapter, we present a simple mechanical model of the bench press to study the importance of the upper limb acceleration in the estimation of the force produced. The moving system (*i.e.*, lifted mass and upper limbs) is modeled from rigid segments and the force can be determined thanks to four simple measurements: the vertical displacement of the lifted load, the elbow angle measured using a goniometer, the arm and forearm lengths and the constant horizontal position of the hand on the barbell. The validity of this model has been confirmed through experimental data obtained from a force platform. An important point is that the kinematics and kinetics of this model allow demonstrating that the acceleration of the moving system is similar to the one of the barbell.

Finally, based on the previous statement, the last part of this chapter presents a simple method for assessing force, velocity and power during a ballistic bench press performed on a traditional guided barbell, based on the Newtonian laws and only three simple parameters: *i)* upper limb mass estimated as 10% of the body mass; *ii)* barbell flight height recorded with a nylon cable tie and *iii)* push-off distance measured with a measuring tape). Consequently, coaches and athletes could accurately determine their F-v profile and extrapolate reliable mechanical parameters (F_0 , v_0 , Sfv and P_{max}) in order to maximize upper limbs performance and manage training programs in field conditions.

7.1 INTRODUCTION

The previous chapters present various simple methods to evaluate muscle power capabilities and F-v profile of lower limbs during ballistic push-off. The majority of studies focusing on lower limbs have been conducted using jumping exercises. While these exercises represent key movements for many sporting activities, upper limbs also have their importance in many activities (e.g., throwing, hitting, and rowing). Different methods have been proposed to assess the upper limb anaerobic abilities including all-out cranking exercises (Vanderthommen. et al. 1997; Driss et al. 1998), medicine ball put test (Stockbrugger and Haennel 2001, 2003) and arm jump (Laffaye et al. 2014). While the validity and reliability of these tests have been attested, the bench press has the advantage to be one of the most common exercises used in training routines by most athletes in many sports. Indeed, bench press is an optimal training movement to increase the anterior trunk (*pectoralis* major and minor), arms (*triceps brachii*) and shoulders (anterior and medial deltoid) (Wilson et al. 1989; Barnett et al. 1995). An increasing interest to the use of the bench press exercise as a simple test for assessing upper limb strength is also observed in the scientific literature (Pearson et al. 2007; Padulo et al. 2012; Buitrago et al. 2013; Sreckovic et al. 2015; García-Ramos et al. 2016).

Two sub-types of bench press exist: the traditional bench press during which the barbell must remain in the hands of the athlete at the end of the propulsive phase of the movement (*i.e.*, the barbell is voluntarily decelerated in order to not throw it), and the ballistic bench press (also called ballistic bench throw) during which the barbell is accelerated during the whole push-off phase inducing a flight phase, as during jumping. Whatever the considered bench press, the muscular parameters of the upper limbs are usually determined using force platforms (Rahmani et al. 2009; Young et al. 2015) or kinematic systems, such as optical encoders (Rambaud et al. 2008; Jandačka and Vaverka 2009) or linear transducers (Garnacho-Castaño et al. 2014; Sreckovic et al. 2015; García-Ramos et al. 2016).

Considering similar loads, the ballistic bench press allows the development of higher values of force, velocity, power and muscle activation in comparison to the traditional one (Newton et al. 1996). The deceleration phase occurring during the traditional bench press exercise seems to be responsible for these results (Cormie et al. 2011). Indeed, Sánchez-Medina et al. (Sanchez-Medina et al. 2010) reported that when light and medium loads are lifted during a traditional bench press, the deceleration at the end of the movement is greater than what would be expected with the unique effect of gravity. The net force applied to the

barbell (which is the mechanical output measured) may so underestimate the force produced by the agonist muscles due to the activation of antagonist muscles, which apply force in the opposite direction to the load motion in order to stop the movement (Jarić et al. 1995). However, the ballistic bench press becomes inadequate when performed with high loads. In this case, the movement is not ballistic anymore and the barbell cannot be thrown. Despite these differences, the force-velocity profiles of both traditional and ballistic bench press are linear, allowing the determination of the parameters evoked in the previous chapters (the theoretical maximal force, velocity and power, and *a fortiori* the individual Sfv). Then, the choice of the type of bench press used for training or testing depends on the goal to achieve. Ballistic bench press is preferred during power training as athletes are able to generate higher values of velocity, force and then power with light to moderate loads. Ballistic bench press can also be considered as more representative of ecological ballistic movements. The traditional bench press is by definition the only one that can be used for high loads and so to evaluate the one repetition maximum (1-RM).

This chapter will focus on the upper limb evaluation from the bench press exercise. First, we will discuss from previous experimental data the importance of taking the upper limb mass into account. Then, a mechanical model of the bench press exercise will be presented to highlight the importance of considering the involved limb segment (*i.e.*, arm and forearm). Finally, a simple method will be detailed to assess the upper limb abilities thanks to only three simple parameters (upper limb mass, barbell flight height and push-off distance) that are easy to measure outside a laboratory and without specific devices.

7.2 THE FORCE, VELOCITY, POWER MECHANICAL PROFILE

7.2.1 Importance of the upper limb inertia during the bench press

As previously mentioned, whatever the considered bench press exercise (*i.e.*, traditional vs. ballistic), the force-velocity (F-v) and power-velocity (P-v) profiles fit linear and second polynomial models, respectively (Figure 7.1) (Rambaud et al. 2008; Sreckovic et al. 2015; García-Ramos et al. 2016). The F-v relationship and explosive maximal power are widely used parameters when studying the mechanical characteristics of muscles or muscle groups. In explosive events like throwing, lower and upper-limb force and maximal power have been evidenced to contribute to the final performance (Bourdin et al. 2010). Determining precisely the maximal power is then important to organize the athlete's training.

It should be kept in mind that mostly all studies used kinematic systems to investigate the muscular power. These systems enable muscular power assessment in terms of lifted load displacement during an exercise. From an external load, and once known its displacement and the time to reach it, mean power is estimated using the Newtonian laws. In order to assess kinematic parameters, the whole mechanical system inertia (*i.e.*, mass of the lifted load plus the inertia of the levers or involved body segments) must be carefully determined to precisely calculate the load at which the power training is optimized (Rambaud et al. 2008). 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 (Winter et al. 1981; Nelson and Duncan 1983; Rahmani et al. 1999). This can lead to an underestimation of the maximal power, maximal force, and maximal velocity extrapolated from the F-v and P-v relationships (Rahmani et al. 1999).

In several bench press studies (Cronin et al. 2000; Shim et al. 2001; Izquierdo et al. 2002; Cronin and Henderson 2004; Sánchez-Medina et al. 2014; García-Ramos et al. 2016), the force was calculated on the basis of load only (*i.e.*, without taking into account the total inertia of the system load plus upper limb mass). This was done “to evaluate the simplest possible approach that can be used for routine testing” (García-Ramos et al. 2016). However, this implies that the upper limb mass and the effort required to accelerate it were neglected, which can, as discussed above, lead to an underestimation of maximal power production. This methodological bias would explain why mean maximal force values obtained in team sport players using kinematic devices (Izquierdo et al. 2002; Cronin et al. 2003) are lower than those measured with a force platform (Wilson et al. 1991a, b, 1994; Murphy et al. 1994).

In order to illustrate this fact, a previous study (Rambaud et al. 2008) aimed at comparing the force calculated from a kinematic encoder to that simultaneously measured with a force platform fixed under the bench (Figure 7.2). The traditional bench press exercise was done under a guided horizontal barbell. Then, we hypothesized that forces produced on the anteroposterior and mediolateral axis could be neglected. The instantaneous velocity and acceleration of the barbell were calculated from successive displacement time-derivatives for each lift. Instantaneous force (F , in N) was calculated as follows:

$$F = M(a + g) + F_f \quad \text{Eq. 7.1}$$

where M is the considered 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 only the lifted load into account (F_{peakb}) or the total moving mass (lifted load plus upper limb mass estimated from Winter's

anthropometric tables (Winter 2009)(F_{peak}). The instantaneous power (in W) was calculated as the product of force and velocity at any given time.

The mean mass of the upper limbs represented about 10% of the total body mass of the subject. Since the lifted masses ranged from 7 to 74 kg, neglecting the upper limb mass has obviously an impact on the force calculation. When the upper limb mass was ignored, the force calculated with the kinematic device, regardless the lifted load, was significantly lower than the one measured with the force platform (Figure 7.3). 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 54% to 10% at 7 and 74 kg, respectively). Considering the upper limb mass in the force calculation, there was no difference between the forces directly measured with the force platform and those calculated from the Newtonian laws. Forces were significantly correlated ($r = 0.91$; $p < 0.001$), close to the identity line (Figure 7.4).

7.2.2 Consequence of the upper limb inertia on the force-velocity profile

Considering or not the upper limb mass, the F-v is significantly linear (figure 7.1a, $r = 0.75-0.98$, $p < 0.05$), and the P-v is significantly described by a second order polynomial regression (Figure 7.1b, $r = 0.88-0.99$, $p < 0.05$). Neglecting the upper limb mass has an impact on the extrapolated force-velocity parameters. The underestimation of F_0 , V_0 , P_{max} and V_{opt} when the upper limb is neglected is equal to 6%, 41%, 32% and 35%, respectively. Even if the difference is significant, the underestimation concerning F_0 is weak. This is due to the relative lower contribution of the upper limb inertia to the total inertia for the heavy lifted loads. The underestimation of P_{max} is more problematic since this parameter is obtained at light lifted loads. The theoretical optimal loads corresponded to a lifted load of 36kg when the upper limb is considered, whereas this optimal load was about twice lower (15kg) when the upper limb mass is neglected. This may have important consequences in explosive training since this kind of training are based on the optimal load at which the maximal power should be addressed (Caiozzo et al. 1981; Kanehisa and Miyashita 1983; Kaneko et al. 1983).

7.3 A SIMPLE MODEL OF THE BENCH PRESS EXERCISE

7.3.1 Importance of the shoulder during the bench press

In the context of the evaluation, the previous section insists on the importance of the upper limb inertia. However, the model used in the previous study considered the upper limb as a punctual mass, moving only vertically. Rambaud et al. (Rambaud et al. 2008) did not give any

information on the upper limb acceleration, and its importance in the force estimation. The bench press exercise involved two joints (the elbow and the shoulder) and several muscular groups (*pectoralis* major and minor, *triceps brachii*, anterior and medial deltoid) which are progressively involved. To dissociate each segment participating in the movement (*i.e.*, arm and forearm) is thus capital to appreciate their respective impact in the whole movement kinematics and dynamics. A first approach was to consider a model of the bench press including only the elbow joint (*i.e.*, the shoulder and the wrist were supposed still) (Figure 7.5). The force could be determined thanks to four simple measurements: the vertical displacement of the lifted load recorded by using a kinematic device, the elbow angle measured using a goniometer, the arm and forearm lengths estimated with the Winter's table (Winter 2009) and the constant horizontal position of the hand on the barbell measured with a tape. However, the computer simulation of the movement evidenced that the sum of the arm and forearm lengths does not reach the maximal height at which the load is lifted (personal data). This implies that the shoulder must be included in the upper limb model (Figure 7.5c).

7.3.2 A simple model based on three segments: shoulder, arm and forearm

Description of the model. Since the bench press exercise was performed with a guided horizontal barbell, actions of the two upper limbs are assumed to be symmetrical. The model had three degrees of freedom. Two revolute joints were used to model the shoulder and elbow rotations, and the vertical shoulder displacement (Z_s) was represented by introducing a prismatic joint (Figure 7.6a). The position of the subject's hands was noted (x_0, Z) . The coordinate x_0 represented the horizontal position of the hand, which was constant because the movement was performed under a vertically guided barbell. Z was the vertical displacement of the barbell and Z_0 was the vertical position of the hand at rest relative to the horizontal axis.

The absolute angles of the upper arm (θ_a) and forearm ($\theta_a + \theta_f$) were expressed relatively 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.

Inverse kinematic model. An inverse kinematic model q was used to calculate the joint coordinates θ_a (in rad) and Z_s (in m) derived from the vertical displacement Z and the elbow angle θ_f :

$$q = \begin{bmatrix} \theta_a \\ \theta_f \\ Z_S \end{bmatrix} \quad \text{Eq. 7.2}$$

θ_a and Z_S were calculated from the hand coordinates which was written as followed:

$$x_0 = L_a \cos \theta_a + L_f \cos(\theta_a + \theta_f) \quad \text{Eq. 7.3}$$

$$Z + Z_0 - Z_S = L_a \sin \theta_a + L_f \sin(\theta_a + \theta_f) \quad \text{Eq. 7.4}$$

where L_a is the length of the upper arm (in m) and L_f is the length of the forearm (in m), both estimated from Winter's table (Winter 2009), Z_0 is the initial vertical position of the hand.

The absolute angle of the arm θ_a (in rad) is derived from Eq. 7.3:

$$\theta_a = \tan^{-1} \left(\frac{Bx_0 + A\sqrt{C - x_0^2}}{Ax_0 + B\sqrt{C - x_0^2}} \right) \quad \text{Eq. 7.5}$$

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

The vertical displacement of the shoulder is derived from Eq. 7.4. Firstly, we need to calculate Z_0 . This can be done geometrically from the rest position (Figure 7.6b). Applying the Pythagoras' theorem in the triangle *SAW* (A is a virtual point allowing to express the distance *SW* from the known distance), we can write:

$$x_0^2 + Z_0^2 = SW^2 \quad \text{Eq. 7.6}$$

The *SW* side of the triangle *SEW* can then be expressed as:

$$SW^2 = L_a^2 + L_f^2 - 2L_a L_f \cos \theta_0$$

From Eq. 8.4 and 8.6, Z_0 can be written as:

$$Z_0 = \sqrt{L_a^2 + L_f^2 - 2L_a L_f \cos \theta_0 - x_0^2} \quad \text{Eq. 7.7}$$

Z_S is then equal to:

$$Z_S = Z + Z_0 - \sqrt{C - x_0^2} \quad \text{Eq. 7.8}$$

For details see Appendix A in (Rahmani et al. 2009)

Acceleration of the combined center of mass. In this model, the human body is considered as two distinct mechanical rigid systems: *i*) the moving system composed of the lifted mass M , the upper limbs (arms and forearms, the hand is not considered) and the shoulders (the mass of the shoulders is neglected); *ii*) the resting system composed of the trunk, the head and the lower limbs, which are considered to remain fixed during the bench press exercise. This latter system is not considered in the force calculation.

To determine the vertical position Z_G of the combined center of mass of the lifted mass, arms and forearms, it is necessary to calculate the vertical position of each center of mass of the element of the moving system (i.e., Z_{G_M} , Z_{G_a} and Z_{G_f} the vertical position of the lifted mass, the arm and the forearm, respectively) ((Figure 7.7a). Z_{G_M} , Z_{G_a} and Z_{G_f} can be written as:

$$Z_{G_M} = Z_S + Z_0 \quad \text{Eq. 7.9}$$

$$Z_{G_a} = Z_S + a_a \sin \theta_a \quad \text{Eq. 7.10}$$

$$Z_{G_f} = Z_S + L_a \sin \theta_a + a_f \sin(\theta_a + \theta_f) \quad \text{Eq. 7.11}$$

where a_a and a_f are the position of the center of mass of the arm and the forearm relatively to the proximal joint, respectively. a_a and a_f were estimated from Winter's table (Winter 2009).

Then, Z_G is expressed as:

$$Z_G = \frac{M(Z+Z_0)+2 m_a Z_{G_a}+2 m_f Z_{G_f}}{m+2 m_a+2 m_f} \quad \text{Eq. 7.12}$$

where m_a and m_f are the arm and forearm masses, respectively, determined from the Winter's anthropometric tables (Winter 2009). Z_G is twice derivated to calculate the acceleration of the combined center of mass acceleration \ddot{Z}_G .

Force calculations. The force F_M produced at the shoulder during the bench press is then determined from the mechanical model ((Figure 7.7b) and expressed as:

$$F_M = M \ddot{Z} + 2 m_a \ddot{Z}_{G_a} + 2 m_f \ddot{Z}_{G_f} + (M + 2 m_a + 2 m_f) g + F_f \quad \text{Eq. 7.13}$$

where \ddot{Z} , \ddot{Z}_{G_a} and \ddot{Z}_{G_f} are the accelerations of the lifted mass M , the arm and forearm segments, respectively and F_f the friction forces. m_a and m_f were multiplied by 2 to take the two upper limbs into account, assuming that the movement was symmetric. Z_{G_M} , Z_{G_a} and Z_{G_f} were twice derivated to determine the accelerations \ddot{Z} , \ddot{Z}_{G_a} and \ddot{Z}_{G_f} , respectively.

7.3.3 Kinematic parameters

The displacement-time courses of the lifted mass Z , the moving system center of mass Z_G , the center of mass of the arm Z_{G_a} and forearm Z_{G_f} and the shoulder Z_S were identical but not equal to Z (Figure 7.8). For a given lifted mass, the vertical difference between Z and Z_G was constant throughout the bench press exercise. Consequently, the vertical velocity and acceleration of the combined center of mass and the lifted mass were identical during the bench press exercise (Figure 7.9). The acceleration determined from the model followed the one measured with the force platform, as it is the case during squat exercise performed under a guided barbell (Rahmani et al. 2000). The difference at the end of the curve is mainly due to the

software treatment (see (Rahmani et al. 2009) for details). However, this part of the curve corresponds to the end of the vertical displacement, when upper limbs are stretched and decelerate the barbell. This part is out of the pushing phase and is not considered in the force calculation. In addition, the difference between Z and Z_G decreases with the increase of the lifted mass. The heavier the lifted mass, the shorter the distance between the centers of mass of the system and of the lifted mass. This is due to the position of the center of mass of the moving system, which is always located close to the greatest mass (*i.e.*, the lifted mass). We can assume that for lifted loads heavier than 74kg, the vertical displacement of Z and Z_G would be superimposed.

Regarding the vertical displacement Z and Z_{G_p} , the difference between them is constant (0.016 ± 0.01 m) for the whole displacement-time curve, whatever the subject or the lifted mass. This result indicates that the elbow extension, mainly performed by the *triceps brachii* at the end of the movement, is too short to influence the centre of mass displacement. The movement of the forearm can then be considered as essentially a translation movement.

The major part of the bench press exercise is due to the arm rotation, performed by the pectoralis major and the anterior deltoid. This is illustrated by the vertical displacement of the arm (Z_{G_a}) and the shoulder (Z_s). Differences between Z and both Z_s and Z_{G_a} followed the same profile whatever the subject or the lifted mass. These differences increase progressively during 65% of the total displacement, describing the removal of the lifted mass with both arm and shoulder. After that, these differences remain constant until the end of the exercise. This instant of the movement corresponds to the alignment of the arms with the forearms. This result was observed for all subjects, whatever the lifted mass.

7.3.4 Kinetic parameters – validation of the model

As mentioned above, the acceleration of the moving system and the one computed from the force platform are identical (Figure 7.9). Consequently, there is no significant difference between the force calculated from the model (F_M) and the one directly measured with the force platform (F_P). The absolute difference between the two values was less than 2.5% considering all the measurements for each lifted mass. The validity of the model is also supported by a coefficient of variation lower than 1% between the two methods. In addition, whatever the lifted mass, F_M is significantly correlated to F_P ($r = 0.99$, $p < 0.001$), with a regression slope not different from unity, and the y-intercept of the linear regression not statistically different from 0 (Figure 7.10).

In order to be complete, F_M is not statistically different from the force estimated by Rambaud et al. (2008) using a kinematic device (see section 7.2) (Table 7.1). An inverse dynamical model is easily constructed using the present model with the experimental results, allowing the determination of joint forces and torques. For this, determination of the acceleration of the arm and forearm is necessary. This kind of model could easily be used by sport scientists to identify the relative importance of each muscle group during bench press exercise, improving the understanding of upper limb injury occurrence and allowing assessing actual rehabilitation program efficiency.

Table 7.1. Mean values (standard deviation) of the force measured with the force platform (F_{PF}), and those estimated with the bench press model (F_M) and using a kinematic device (F_K) (as presented section 8.2)

Mass (kg)	F_{PF} (N)	F_M (N)	F_K (N)
24	621 ± 99	619 ± 97	620 ± 95
34	694 ± 95	697 ± 95	698 ± 96
44	805 ± 85	804 ± 85	804 ± 86
54	829 ± 108	829 ± 109	827 ± 105
64	875 ± 102	875 ± 103	875 ± 101
74	942 ± 91	943 ± 91	943 ± 93

7.4 A SIMPLE METHOD MEASURING FORCE, VELOCITY AND POWER DURING THE BENCH PRESS EXERCISE

7.4.1 Theoretical bases and equations

This method (Rahmani et al. 2017) is based on the simple method developed by Samozino et al. 2008 during squat jump (see chapter 4). So, only three simple parameters are required for these computations: the mass of the studied system (*i.e.*, upper limbs plus lifted mass), the vertical displacement during the freefall phase (h) and the vertical push-off distance (h_{po}) extracted from a ballistic bench press (Figure 7.11). The previous assumptions are applied to this method: the acceleration of the barbell is representative of the studied system's acceleration and the mass of the upper limbs are taken into account in the calculation of the force produced.

Since the movement is performed on a guided barbell machine with a friction force, the acceleration during the freefall (a_{ff}) is not the gravitational acceleration. Assuming the friction force is constant during the freefall, a_{ff} can be estimated with the second law of Newton as:

$$a_{ff} = \frac{g.m_b + F_f}{m_b} \quad \text{Eq. 7.14}$$

Substituting g by a_{ff} in the equation 4 and 8 of Samozino et al. (2008) gives:

$$\bar{F} = m_{ul+b} \times \frac{g.m_b + F_f}{m_b} \times \left(\frac{h}{h_{po}} + 1 \right) \quad \text{Eq. 7.15}$$

$$\bar{v} = \sqrt{\frac{\frac{g.m_b + F_f}{m_b} \times h}{2}} \quad \text{Eq. 7.16}$$

In this method, h is measured with a nylon cable tie fixed around the rail of the guided barbell machine (Figure 7.12) which allows a reading of the highest height attained by the barbell. This tie is moved upwards along the rail as the barbell is thrown by the athletes, but stays still in its maximal height position as the barbell moves downwards. Finally, h_{po} is measured as the difference between the initial position of the barbell (*i.e.*, in contact with the security catches) and the maximal height attained at the end of the push-off (Figure 7.11). All the dimensions can be measured using a non-flexible tape, with 0.1 cm accuracy.

Calculating force and velocity following Eq. 7.15 and 7.16 for bench press performed at different additional loads gives different points of the force-velocity relationship: the higher the moving mass (upper limbs mass + barbell mass), the higher the force and the lower the velocity, as during squat jump. F-v curves were then extrapolated to obtain F_0 and v_0 , which corresponds to the intercepts of the F-v curve with the force and the velocity axis, respectively. The slope of the F-v linear relationship (Sfv) was also considered for further analysis. Values of maximal power of the power-velocity relationship (P_{max}) were calculated as previously validated (Vandewalle et al. 1987; Samozino et al. 2012):

$$P_{max} = \frac{F_0 \times v_0}{4} \quad \text{Eq. 7.17}$$

7.4.2 Validation of the method

The validity of the computation method was established by comparing *i)* \bar{F} and \bar{v} obtained from the computation method to those simultaneously measured with an accelerometer (Myotest® Pro; Myotest SA, Sion, Switzerland) fixed on the barbell; and *ii)* the mechanical parameters extrapolated from the F-v relationships (*i.e.*, F_0 , V_0 , Sfv , and P_{max}) obtained from these two methods. In this study, twelve healthy and physically active males performed two ballistic bench presses at different loads (30, 40, 50, 60 and 70% of body mass). Regarding the results, the validity of the method is supported by the almost perfect relationships observed for the force ($r = 0.95$, $p < 0.001$) and the velocity ($r = 0.89$, $p < 0.001$) estimated by the two

methods. The equations of the regression lines were not different from that of the identity line. The magnitude of the correlation observed for the force was in line with those observed during squat and countermovement jumps (r from 0.95 to 1) (Samozino et al. 2008; Giroux et al. 2014; Jiménez-Reyes et al. 2017). For the velocity, the coefficient of correlation is slightly lower than those obtained for the force, again as previously observed during squat jumps (0.87 to 0.94) (Giroux et al. 2014). Nevertheless, there is no difference between the force and the velocity measured by the two methods (systematic bias is around 30N for the force, and $0.07\text{m}\cdot\text{s}^{-1}$ for the velocity; $\text{CV}\% < 10\%$). In addition, very high between-trials reliability was found for a given load by the intraclass coefficient of correlation (ICC) higher than 0.8 for force and velocity, which is in line with those reported in previous studies focusing on ballistic bench press (Alemany et al. 2005) and classical bench press exercise (Comstock et al. 2011; Garnacho-Castaño et al. 2014). The $\text{CV}\%$ here obtained suggested adequate absolute reliability (*i.e.*, $<10\%$) for \bar{F} and \bar{v} (ranging from 0.8 to 1.7% and 1.4 to 6.3%, respectively), in agreement with previous studies mentioned above. Thus, these results evidenced high between-trials reliability for the computation method.

Finally, in agreement with the accelerometer method, the relation between force and velocity estimated by the simple method was well described by a negative linear relationship (Figure 7.13), as it was previously shown for classical bench press (Rambaud et al. 2008; García-Ramos et al. 2015) and bench throw (Sreckovic et al. 2015; García-Ramos et al. 2016). The validity of the simple method was supported by the strong correlations of the force-velocity slope ($r^2=0.99$, $p<0.001$), F_0 ($r^2=0.93$, $p<0.001$), v_0 ($r^2=0.59$, $p<0.05$), and P_{\max} ($r^2=0.87$, $p<0.001$; all not different from unity).

7.4.3 Limits of the method

To validate the method, the force and velocity estimated from Eq. 7.15 and 7.16 was compared to the measure simultaneously obtained with an accelerometer, instead of a force platform (referred as the ‘gold standard’). This choice was done because the accelerometer directly measures the motion of the lifted barbell, including the flight phase. The use of a force platform presents two main disadvantages. Firstly, during ballistic bench throws, the moving system (upper limbs and lifted mass) is split in two separate systems at the release. This makes difficult to track the true moment of release in opposition to what happened during squat jump (the force platform signal is null). Secondly, a force platform monitors all the reaction forces occurring during the movement, also those produced from “parasite contractions” (*e.g.*, lower limbs movement, abdominal muscles contraction), making difficult

to estimate the net force applied to the moving system. Using an accelerometer has the advantage to determine precisely at which time the barbell is thrown and to estimate only the force developed by the upper limbs to accelerate the system (Comstock et al. 2011).

Another limitation concerns the necessity to estimate the friction force due to the guided barbell system into account. Since the bench presses were performed under a vertical guided barbell, it seems important to take all the mechanical parameters into account, and also the friction force (F_f) due to the guided barbell system. We acknowledge that some coaches may not be familiar with the procedure to determine F_f but, unfortunately, by neglecting F_f , errors on the F-v parameters could occur, even if more modern machines present lower friction forces. The force-velocity profiles including or not F_f in the computations for a typical individual are depicted in Figure 7.13. Considering the whole experimental population, V_o is overestimated by $16 \pm 6 \%$, F_o is underestimated by $5 \pm 5 \%$ and the Sfv is underestimated by $25 \pm 10 \%$. Such a bias is important to consider during bench press since the lifted mass (including the upper limb mass) is low in comparison to the one lifted during a loaded squat. Another way to say it is that the proportion of the friction force is high when considering the sum of the forces applied to the system during a bench press. In the present study, the ratio between F_f and the total lifted mass ranges between 24% (for the lightest lifted load) and 10% (for the heaviest one). The variation of the ratio with the lifted loads explains why the estimation of the slope is the most affected when F_f is neglected. In comparison, if the studied movement was a squat, this ratio would be ranged between 5% (for the heaviest one) to 6% (for the lightest lifted load) which can explain why F_f is generally neglected in this case. Fortunately, the acceleration of the friction losses (a_{Ff}) can easily be determined by measuring the time during which the barbell is falling on a given displacement d . It can be assumed that the friction forces are constant during the falling test. So, a_{Ff} could also be considered as constant and is equal to:

$$a_{Ff} = \frac{2 \cdot d}{t^2} \quad \text{Eq. 7.18}$$

The time t can be easily measured using a smartphone, including the build-in camera with a 240-Hz sampling rate, which allows to measure the time with a sufficient accuracy and d with a non-flexible measuring tape.

7.4.4 Practical applications

The model used here is identical to the one previously proposed on jump (see chapter 4) and present the same practical application as those discussed in these studies (*i.e.*, maximizing

power production). In the same way, (García-Ramos et al. 2016) observed that the F_0 is strongly correlated with the 1-RM measured during a bench press exercise ($r=0.92-0.94$). The force-velocity relationship is then useful to assess the upper-body maximal capabilities to generate force, velocity, and power.

Warm up. As indicated in chapter 5, after 5 to 10 minutes of a typical general warm-up (e.g., running or cycling), specific warm-up has to include ballistic bench throws with a progressive increase in the intensity (for example: 10 submaximal reps at 20 kg, 8 at 30 kg, 6 at 40 kg, 4 at 50kg, 3 at 60 kg, 2 at 70 kg). Throwing the barbell with the upper limb is not a “natural” movement, and apprehension of this type of movement should be eliminated to ensure the best conditions for assessing objectively the force and power abilities of an individual. Obviously a familiarization session should be scheduled if athletes are not accustomed to ballistic bench press.

Push-off distance. A major concern should be addressed to correctly determine the push-off distance (h_{po}). Participants laid supine on the bench. The barbell was positioned across their chest at nipple level above the *pectoralis major*, supported by the lower mechanical stops of the measurement device (≈ 5 cm above the chest). Participants held the barbell choosing the most comfortable position. This handgrip was determined during the warm-up and must be marked on the barbell with tape to ensure reproducibility. h_{po} was measured as the difference between the initial position of the barbell (i.e., in contact with the security catches) and the maximal height attained after the push-off (Figure 7-11). To reach this latter distance, participants were asked to tense maximally their upper limb, including the shoulder antepulsion. The movement should be done as smoothly as possible and the back should stay in contact with the bench.

Starting position. During the validation of the method, participants were asked to cross their legs to standardize the position and to avoid the influence of the ground reaction force resulting from lower limbs pushing on the floor. This is recommended during testing but is not mandatory during real training which can be done as desired. That being said, since the method is based on the h_{po} measured under a guided barbell, the force, velocity and power determination remains identical whatever the considered starting position. A practical point that should be taken into account may concern the starting position of the barbell. This one is generally positioned across the individual’s chest at nipple level above the *pectoralis major* (\approx

5 cm above the chest). It could be preferable to start the ballistic bench press from a higher height (a comfortable height such as 10 or 15 cm). In this way, the athlete is in a more comfortable and optimal position to overcome the greatest inertia mainly encountered at the beginning of the movement (especially, for the heaviest lifted loads or for participants who are not accustomed to ballistic bench press).

Individualization of training. Considering strength training programs, the simple method proposed here for the bench press can be used to compare athletes, to monitor, and to individualize training from their F-v profile and the requirements of the task. Figure 7.14 shows very high differences in F-v relationships among players of the same age with a higher variability in V_0 than in F_0 values. We can observe that players who presented the highest maximal force (F_0) were not those who produced the highest force at high movement velocities (V_0). When strength training aims at improving ballistic upper limb extensions (e.g., to improve explosive passes or long distance shots), it is more efficient to focus on increasing V_0 than F_0 , notably given that a basket ball weighs ~600 g. So, in this context, players who present high F_0 values need velocity based strength training. Conversely, players with high V_0 values should follow training focusing on the entire F-v spectrum. This highlights the large interest for sport practitioners to determine F-v profiles for individualizing strength training of upper limbs.

7.5 CONCLUSION

This chapter presents simple methods to evaluate the upper limb force during bench press exercise. A particular attention should be brought to the different inertia involved during the bench press exercise. To neglect the upper limb mass in the force calculation leads to an underestimation of the force, and *a fortiori* of the maximal power an individual can produce. This has the consequence of underestimating the optimal load at which the training program should be performed.

A simple model of the bench press exercise demonstrates that the acceleration of the moving system (lifted mass plus upper limb mass) is similar to the acceleration of the barbell. Consequently, the inverse kinetic model demonstrated a great validity in the force estimation thanks to four simple measurements: the vertical displacement of the lifted load, the elbow angle, the lengths of the arm and forearm and the horizontal position of the hand. The comparison of the force calculated from this model and the one measured with a force platform shows no significant difference between the two scores.

This leads to evaluate a simple method to assess the force, velocity and power produced during a ballistic bench press performed outside a laboratory, thanks to the Newtonian laws and only three simple parameters: *i)* the upper limb mass estimated as 10% of the body mass, *ii)* the barbell flight height recorded thanks to a nylon cable tie and *iii)* the push-off distance measured with a measuring tape. The method developed for jumping exercise is also valid to estimate the mechanical properties of the upper limb with only slight adaptations (i.e. taking into account the upper limb mass and friction forces). Consequently, coaches and athletes could accurately determine their F-v profiles, extrapolate reliable mechanical parameters (F_0 , V_0 , Sfv and P_{max}) in order to maximize upper limbs performance and manage and individualize training programs in field conditions.

7.6 REFERENCES

- Aleman JA, Pandorf CE, Montain SJ, Castellani JW, Tuckow AP, Nindl BC (2005) Reliability assessment of ballistic jump squats and bench throws. *J Strength Cond Res* 19:33–38. doi: 10.1519/14783.1
- Barnett C, Kippers V, Turner P (1995) Effects of Variations of the Bench Press Exercise on the EMG Activity of Five Shoulder Muscles. *J Strength Cond Res* 9:222–227. doi: 10.1519/00124278-199511000-00003
- Bourdin M, Rambaud O, Dorel S, Lacour JR, Moyon B, Rahmani A (2010) Throwing performance is associated with muscular power. *Int J Sports Med* 31:505–510. doi: 10.1055/s-0030-1249622
- Buitrago S, Wirtz N, Yue Z, Klienider H, Mester J (2013) Mechanical load and physiological responses of four different resistance training methods in bench press exercise. *J strength and Cond Res* 27:1091-1100.
- Caiozzo VJ, Perrine JJ, Edgerton VR (1981) Training-induced alterations of the in vivo force-velocity relationship of human muscle. *J Appl Physiol* 51:750–4.
- Comstock BA, Solomon-Hill G, Flanagan SD, Earp JE, Luk HY, Dobbins KA, Dunn-Lewis C, Fragala MS, Ho J-Y, Hatfield DL, Vingren JK, Denegar CR, Volek JS, Kupchak BR, Maresh CM, Kraemer WJ (2011) Validity of the Myotest in measuring force and power production in the squat and bench press. *J Strength Cond Res* 25:2293–2297.
- Cormie P, McGuigan MR, Newton RU (2011) Developing maximal neuromuscular power: Part 2 training considerations for improving maximal power production. *Sport Med* 41:125–146. doi: 10.2165/11538500-000000000-00000
- Cronin JB, Henderson ME (2004) Maximal strength and power assessment in novice weight trainers. *J Strength Cond Res* 18:48–52.
- Cronin JB, McNair PJ, Marshall RN (2000) The role of maximal strength and load on initial power production. *Med Sci Sports Exerc* 32:1763–1769. doi: 10.1097/00005768-200010000-00016
- Cronin JB, McNair PJ, Marshall RN (2003) Force-Velocity Analysis of Strength-Training Techniques and Load: Implications for Training Strategy and Research. *J Strength Cond Res* 17:148. doi: 10.1519/1533-4287(2003)017<0148:FVAOST>2.0.CO;2
- Driss T, Vandewalle H, Monod H (1998) Maximal power and force-velocity relationships during cycling and cranking exercises in volleyball players: Correlation with the vertical jump test. *J Sports Med Phys Fitness* 38:286–293.
- García-Ramos A, Jaric S, Padial P, Feriche B (2016) Force-velocity relationship of upper body

- muscles: Traditional versus ballistic bench press. *J Appl Biomech* 32:178–185. doi: 10.1123/jab.2015-0162
- García-Ramos A, Jaric S, Padial P, Feriche B (2015) Force-Velocity Relationship of Upper-Body Muscles: Traditional vs. Ballistic Bench Press. *J Appl Biomech* 1–44. doi: 10.1123/jab.2015-0162
- Garnacho-Castaño M V., López-Lastra S, Maté-Muñoz JL (2014) Reliability and validity assessment of a linear position transducer. *J Sport Sci Med* 14:128–136.
- Giroux C, Rabita G, Chollet D, Guilhem G (2014) What is the best method for assessing lower limb force-velocity relationship? *Int J Sports Med* 36:143–149. doi: 10.1055/s-0034-1385886
- Izquierdo M, Häkkinen K, Gonzalez-Badillo JJ, Ibanez J, Gorostiaga EM (2002) Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. *Eur J Appl Physiol* 87:264–271. doi: 10.1007/s00421-002-0628-y
- Jandačka D, Vaverka F (2009) Validity of Mechanical Power Output Measurement at Bench Press Exercise. *J Hum Kinet* 21:33–40. doi: 10.2478/v10078
- Jarić S, Ropret R, Kukolj M, Ilić DB (1995) Role of agonist and antagonist muscle strength in performance of rapid movements. *Eur J Appl Physiol Occup Physiol* 71:464–468. doi: 10.1007/BF00635882
- Jiménez-Reyes P, Samozino P, Pareja-Blanco F, Conceição F, Cuadrado-Penafiel V, Gonzales-Badillo JJ, Morin JB (2017) Validity of a simple method for measuring force-velocity-power profile in countermovement jump. *Int J Sports Physiol Perform* 12:36–43. doi: 10.1123/IJSPP.2015-0484
- Kanehisa H, Miyashita M (1983) Specificity of velocity in strength training. *Eur J Appl Physiol Occup Physiol* 52:104–106. doi: 10.1007/BF00429034
- Kaneko M, Fuchimoto T, Toji H, Suei K (1983) Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scand J Sport Sci* 5:50–55.
- Laffaye G, Collin JM, Levernier G, Padulo J (2014) Upper-limb power test in rock-climbing. *Int J Sports Med* 35:670–675. doi: 10.1055/s-0033-1358473
- Murphy AJ, Wilson GJ, Pryor JF (1994) Use of the iso-inertial force mass relationship in the prediction of dynamic human performance. *Eur J Appl Physiol Occup Physiol* 69:250–257. doi: 10.1007/BF01094797
- Nelson SG, Duncan PW (1983) Correction of isokinetic and isometric torque recordings for the effects of gravity. A clinical report. *Phys Ther* 63:674–676.
- Newton RU, Kraemer WJ, Häkkinen K, Humphries BJ, Murphy AJ (1996) Kinematics, kinetics, and muscle activation during explosive upper body movements. *J Appl Biomech* 12:37–43.
- Padulo J, Mignogna P, Mignardi S, Tonni F, D'Ottavio S (2012) Effect of different pushing speeds on bench press. *Int J Sports Med* 33:376–380. doi: 10.1055/s-0031-1299702
- Pearson S, Cronin J, Hume P, Slyfield D (2007) Kinematic and kinetics of the bench press and bench pull exercises in a strength trained sporting population. *Symp A Q J Mod Foreign Lit* 27–30.
- Rahmani A, Belli A, Kostka T, Dalleau G, Bonnefoy M, Lacour J-R (1999) Evaluation of knee extensor muscles under non-isokinetic conditions in elderly subjects. *J Appl Biomech* 15:337–344. doi: 10.1123/jab.15.3.337
- Rahmani A, Dalleau G, Viale F, Hautier CA, Lacour J-R (2000) Validity and reliability of a kinematic device for measuring the force developed during squatting. *J Appl Biomech* 16:26–35.
- Rahmani A, Rambaud O, Bourdin M, Mariot JP (2009) A virtual model of the bench press

- exercise. *J Biomech* 42:1610–1615. doi: 10.1016/j.jbiomech.2009.04.036
- Rahmani A, Samozino P, Morin J-B, Morel B (2017) A Simple Method for Assessing Upper Limb Force-Velocity Profile in Bench Press. *Int J Sports Physiol Perform* 1–23. doi: 10.1123/ijssp.2016-0814
- Rambaud O, Rahmani A, Moyon B, Bourdin M (2008) Importance of upper-limb inertia in calculating concentric bench press force. *J Strength Cond Res* 22:383–389. doi: 10.1519/JSC.0b013e31816193e7
- Samozino P, Morin JB, Hintzy F, Belli A (2008) A simple method for measuring force, velocity and power output during squat jump. *J Biomech* 41:2940–2945. doi: 10.1016/j.jbiomech.2008.07.028
- Samozino P, Rejc E, Di Prampero PE, Belli A, Morin JB (2012) Optimal force-velocity profile in ballistic movements-Altius: Citius or Fortius? *Med Sci Sports Exerc* 44:313–322. doi: 10.1249/MSS.0b013e31822d757a
- Sánchez-Medina L, González-Badillo JJ, Pérez CE, Pallarés JG (2014) Velocity- and power-load relationships of the bench pull vs Bench press exercises. *Int J Sports Med* 35:209–216. doi: 10.1055/s-0033-1351252
- Sanchez-Medina L, Perez CE, Gonzalez-Badillo JJ (2010) Importance of the propulsive phase in strength assessment. *Int J Sports Med* 31:123–129. doi: 10.1055/s-0029-1242815
- Shim a L, Bailey ML, Westings SH (2001) Development of a field test for upper-body power. *J Strength Cond Res* 15:192–197. doi: 10.1519/1533-4287(2001)015<0192:DOAFTF>2.0.CO;2
- Sreckovic S, Cuk I, Djuric S, Nedeljkovic A, Mirkov D, Jaric S (2015) Evaluation of force-velocity and power-velocity relationship of arm muscles. *Eur J Appl Physiol* 115:1779–1787. doi: 10.1007/s00421-015-3165-1
- Stockbrugger B, Haennel RG (2001) Validity and reliability of a medicine ball explosive power test. *J Strength Cond Res* 15:431–438. doi: 10.1519/1533-4287(2001)015<0431:VAROAM>2.0.CO;2
- Stockbrugger B, Haennel R (2003) Contributing factors to performance of a medicine ball explosive power test: a comparison between jump and nonjump athletes. *J Strength Cond Res* 17:768–774. doi: 10.1519/1533-4287(2003)017<0768:CFTPOA>2.0.CO;2
- Vanderthommen M, Francaux M, Johnson D, Dewan M, Lewyckyj Y, Sturbois X (1997) Measurement of the power output during the acceleration phase of all-out arm cranking exercise. *Int. J. Sports Med.* 18:600–606.
- Vandewalle H, Peres G, Heller J, Panel J, Monod H (1987) Force-velocity relationship and maximal power on a cycle ergometer - Correlation with the height of a vertical jump. *Eur J Appl Physiol Occup Physiol* 56:650–656. doi: 10.1007/BF00424805
- Wilson G, Elliott BC, Kerr GK (1989) Bar Path and Force Profile Characteristics for Maximal and Submaximal Loads in the Bench Press. *Int J Sport Biomech* 21:450–462. doi: 10.1123/ijspb.5.4.390
- Wilson GJ, Elliott BC, Wood GA (1991a) The effect on performance of imposing a delay during a stretch-shorten cycle movement. *Med Sci Sport Exerc* 23:364–370. doi: 10.1249/00005768-199103000-00016
- Wilson GJ, Murphy AJ, Pryor JF (1994) Musculotendinous stiffness: its relationship to eccentric, isometric, and concentric performance. *J Appl Physiol* 76:2714–9.
- Wilson GJ, Wood G a, Elliott BC (1991b) Optimal stiffness of series elastic component in a stretch-shorten cycle activity. *J Appl Physiol* 70:825–833.
- Winter DA (2009) *Biomechanics and Motor Control of Human Movement*.
- Winter DA, Wells RP, Orr GW (1981) Errors in the use of isokinetic dynamometers. *Eur J Appl Physiol Occup Physiol* 46:397–408. doi: 10.1007/BF00422127

Young KP, Haff GG, Newton RU, Gabbett TJ, Sheppard JM (2015) Assessment and monitoring of ballistic and maximal upper-body strength qualities in athletes. *Int J Sports Physiol Perform* 10:232–237. doi: 10.1123/ijsp.2014-0073