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INVITED COMMENTARY

Is the Concept, Method, or Measurement to Blame for Testing Error? An Illustration Using the Force-Velocity-Power Profile

**Pierre Samozino,[1] Jean Romain Rivière,[1] Pedro Jimenez-Reyes,[2]
Matt R. Cross,[3] and Jean-Benoît Morin[3,4]**

[1]Univ Savoie Mont Blanc, Interuniversity Laboratory of Human Movement Sciences, EA 7424, Chambéry, France; [2]Center for Sport Studies, Rey Juan Carlos University, Madrid, Spain; [3]Sports Performance Research Institute New Zealand (SPRINZ), Auckland University of Technology, Auckland, New Zealand; [4]UJM-Saint-Etienne, Université de Lyon, Interuniversity Laboratory of Human Movement Sciences, EA 7424, Saint-Etienne, France

When poor reliability of "output" variables is reported, it can be difficult to discern whether blame lies with the measurement (ie, the inputs) or the overarching concept. This commentary addresses this issue, using the force-velocity-power (FvP) profile in jumping to illustrate the interplay between concept, method, and measurement reliability. While FvP testing has risen in popularity and accessibility, some studies have challenged the reliability and subsequent utility of the concept itself without clearly considering the potential for imprecise procedures to impact reliability measures. To this end, simulations based on virtual athletes confirmed that push-off distance and jump-height variability should be <4% to 5% to guarantee well-fitted force–velocity relationships and acceptable typical error (<10%) in FvP outputs, which was in line with previous experimental findings. Thus, while arguably acceptable in isolation, the 5% to 10% variability in push-off distance or jump height reported in the critiquing studies suggests that their methods were not reliable enough (lack of familiarization, inaccurate procedures, or submaximal efforts) to infer underpinning force-production capacities. Instead of challenging only the concept of FvP relationship testing, an alternative conclusion should have considered the context in which the results were observed: If procedures' and/or tasks' execution is too variable, FvP outputs will be unreliable. As for some other neuromuscular or physiological testing, the FvP relationship, which magnifies measurement errors, is unreliable when the input measurements or testing procedures are inaccurate independently from the method or concept used. Field "simple" methods require the same methodological rigor as "lab" methods to obtain reliable output data.

Keywords*:* reliability, validity, reproducibility, strength evaluation, jumping

With recent technological and methodological innovation, complicated biomechanical and physiological testing protocols once restricted to well-funded research laboratories are now feasible in field conditions for athlete testing, training, rehabilitation, and applied research. Importantly, although accessibility has markedly increased in parallel to perceivable drops in assessment complexity, the intricacy of underlying physiological, neuromuscular, or biomechanical variables has remained constant across field and laboratory methods. Unfortunately, distinguishing measurement reliability from the relevance of the overarching concept can be difficult when poor reliability of "output" variables is reported in research conclusions and potentially ascribed to the physiological/biomechanical concepts or computation methods themselves. The practical value of various measurements and implementations are certainly owed attention and critique within research; however, imprecise analyses and subsequent narrative can complicate consensus on their true utility. A more balanced approach should include critical examination of *all* sources of error, notably, input data collection and the rigor of associated procedures, device (in)accuracy, and the variability of the athletes' effort tested (biological error).

Although this phenomenon exists in every kind of physiological or biomechanical assessment, this commentary focuses on the reliability of force-velocity-power (FvP) relationship in jumping. This is a pertinent focus given the increasing use of the century-old force–velocity (Fv) relationship concept and associated variables in research[1] and the fact that 3 recent studies have challenged the reliability and subsequent utility of FvP profiling.[2–4] Unfortunately, these studies give little to no consideration in their conclusions to an obvious source for their insufficient low measurement reliability or procedures standardization. Are FvP relationships and associated individual "profile" concepts fundamentally flawed and the associated testing methods unreliable (as often concluded in these studies), or is it also (and to what extent) an issue with the input data measurements?

This commentary paper discusses the distinction between measurement reliability, model or method validity, and concept relevance using the FvP profile in jumping as an illustration. The narrative is based on published results and accessible data sets examining reliability of jumping FvP profiles (both inputs and outputs) and on theoretical simulations that estimate the random error of output variables induced by increasing the variability of input measurements.

Reliability of FvP Profile Variables: Experimental Results

First, what is commonly termed the "FvP profile," "FvP profiling," or "FvP variables" and refers to a test of strength qualities

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Rivière https://orcid.org/0000-0002-4878-3601
Jimenez-Reyes https://orcid.org/0000-0002-8156-243X
Cross https://orcid.org/0000-0003-1579-3720
Morin https://orcid.org/0000-0003-3808-6762
Samozino (Pierre.samozino@univ-smb.fr) is corresponding author, https://orcid.org/0000-0002-1665-870X

represents, in fact, an extraction of indices (eg, maximal theoretical force [F_0] and velocity [v_0], maximal power output [P_{max}], slope of the Fv relationship [S_{Fv}]) from fundamental principles of muscle physiology. The Fv relationship describes the force production capacities of the neuromuscular system per contraction/movement velocity.[1,5–7] This relationship has been observed for almost a century on in vitro isolated muscles[1] and in vivo single-joint (eg, knee extension[6]), multijoint (eg, cycling,[7] jumping,[8] leg pressing[9] and bench pressing[10]), and whole-body (eg, rowing[11] and sprinting[12]) movements. Although the methods or models used to determine this relationship are open to discussion, their physiological bases are robust. In any case, several research groups have reported mostly acceptable to good validity or reliability of the main jumping FvP relationship outputs across different methods, including "gold standard" force plates and dynamics principles[8,13–17] and computation-based field methods using inverse dynamics approaches[14–16,18,19] (Tables 1 and 2).

In contrast, 3 recent studies have reported poor reliability of FvP profile outputs (notably v_0 and S_{Fv}) obtained during jumping using various methods, including computation-based and reference methods.[2–4] The interpretations and conclusions provided by the authors clearly challenge both the methods and the FvP concept relevance: "The squat jump Fv [. . .] profiles established with a force plate are not reliable. Therefore, these profiles are not recommended to be used to inform programming decisions,"[4] and "Coaches and researchers should be aware of the poor reliability of the Fv variables obtained from vertical jumping,"[2] or "Fv variables [. . .] seemed to present a low between-day reliability."[3] Unfortunately, input measurement reliability and questionable testing procedures are largely overlooked as a potential cause of error in the "take-home" messages and conclusions.

The reliability of outcome variables in Fv relationships (and all testing protocols) varies as a function of their input measurements. To this end, there are several clear issues with the papers discussed earlier, including: mixing constrained and unconstrained movements within the same testing, lacking participant familiarity with unloaded/loaded jumps, large and potentially fatiguing testing volumes, inconsistent starting position (and so range of motion, h_{po}), and variable jump height (h) between test and retest (Table 1). For example, Valenzuela et al[3] reported a starting position with an approximate resolution of ±1 to 3 cm and Lindberg et al[2] a variability of 2 to 4 cm (ie, 5%–10%). Although the authors discussed this point as a potential explanation of their inferior reliability compared with previous studies, they still concluded that Fv profile variables are *themselves* generally unreliable. Of greater concern, Lindberg et al[2] reported that intersession variability of h without additional load was *on average* 4.9% to 6.4% (ie, 1.9–2.5 cm) with 25% of the subjects exhibiting variability >8%[2] (Figure 1). Comparable variability was reported by Kotani et al[4] (~3.5 cm; ~10%) and Valenzuela et al[3] (~2.4 cm; ~7.8%). Note that some of these variabilities (eg, when < ~10%) can be acceptable when each measurement constitutes a strength output per se, independently and separately from the others, but can be too high when they are combined together in case of more integrative indexes based on several measurements in different conditions, as here for FvP profile variables. Both poorly standardized testing procedures and biological error can explain intersession variability in h, but in either case, the Fv relationship concept and the associated computational methods are not the (only) cause of output variability. The biological variation in ballistic capacity (ie, h) between 2 sessions is an interesting and important point to consider for FvP profiling in jumping; nevertheless, it was largely overlooked within abstracts and conclusions of these papers as a core explanation for poor reliability. Given the consistent acceptable reliability in jumping FvP relationships reported by various independent research groups[8,13–16] (Table 2), an alternative conclusion should have considered the context in which the results were observed: If input data are highly variable—caused by poor testing procedures (eg, associated with field testing) or large biological variation (eg, population or context specific)—FvP outputs will be unreliable. This would have been *the* important message for sport practitioners.

More surprisingly, after concluding that FvP profile variables in jumping are unreliable,[2] and subsequently cautioning their use, the same authors published a training study aiming to improve physical performance measures based on athletes' strengths and weaknesses per an FvP profiling approach.[20] Their results (based on unreliable indices, per their previously published work) clearly contrast previous studies[21,22] and lead to confusing conclusions: They challenged the interest of considering the FvP profile in strength training without challenging the reliability of the indices on which training was individualized. In addition to affecting the reliability, a high variability in h_{po} can also affect the concurrent validity when comparing force plate measurements with computation method using a priori determined h_{po} values. For instance, Hicks et al[23] reported high reliability in FvP outputs obtained from the computation method but lower concurrent validity with gold standard for some variables, which can be partly explained by the 4% to 5% variability observed in h_{po}.[23]

Sensitivity of FvP Profile Variables to Measurement Noise: Theoretical Simulation

Given the apparent confusion on this topic, we set out to clearly illustrate the association between input (procedure reliability) and output error. To this end, we generated a range of theoretical simulations of FvP outputs based on a validated biomechanical model of jumping.[14,17,18,24] Our aim was to quantify the range in error in kinetic output variables (F_0, v_0, P_{max}, and S_{Fv}) that might arise from noise in the 2 main kinematic input measurements (h_{po} and h, their magnitude drawn from previous studies). Note that if h_{po} and h are the 2 main inputs (in addition to body mass),[24] they represent indices of procedural rigor independent from the FvP profile concept itself: h_{po} variability informs quality of task standardization, and h variability is associated with biological variation in performance, including variability caused by limited familiarization or submaximal intent. Moreover, the results of these simulations are broadly applicable as variability in h or squat depth is inevitably associated with error in FvP variables, whichever method is used to obtain them.

Theoretical simulations were based on 3000 virtual athletes (with F_0 from 20 to 40 N/kg, v_0 from 2 to 6 m/s, P_{max} from 16 to 50 W/kg, and h_{po} from 0.25 to 0.45 m) performing 2 FvP jump tests with 5 loads (0%, 25%, 50%, 75%, and 100% body mass). The first simulated test was considered "perfect" (Fv curve $r^2 = 1$): h obtained for each load was estimated from individual Fv relationships, body mass, and h_{po} values.[17] In the second simulated test, random errors were included in h_{po} (simulating errors in squat depth standardization) and h for each loading condition (simulating biological variability) with different noise magnitudes: averaged raw error over all virtual subjects from 0 to 4.5 cm for h_{po} and h (ie, coefficient of variation from 0% to ~13%). From these h and h_{po} values, push-off averaged force, velocity, and power were estimated and used to determine individual Fv relationships of the

Table 1 Methods and Variability of Force–Velocity Profile “Input” Variables in Previous Studies

	Methods					Input variable					
						h_{po}			Unloaded/loaded jump height		
	Device	Reliability	Measurement	Jump type	Range of loads	SEM, cm	CV	ICC	SEM, cm	CV	ICC
Cuk et al[8]	Pully device	Interday	Force plate	SJ	−30% to + 30% BM	—	—	—	—	—	—
				CMJ		—	—	—	—	—	—
Garcia-Ramos et al[13]	Free weights	Interday	Force plate	SJ	0 to 75 kg	—	—	—	—	—	—
	Smith machine					—	—	—	—	—	—
	Free weights			CMJ		—	—	—	—	—	—
	Smith machine					—	—	—	—	—	—
Jimenez-Reyes et al[16]	Free weights	Intraday	Force plate	CMJ	—	—	—	—	—	—	—
			Computation-based method			—					
Janicijevic et al[15]	Free weights	Intraday	Force plate	SJ	0.5 to ~61 (±12) kg	—	—	—	—	—	—
						—	—	—	—	—	—
	Free weights	Intraday	Computation-based method		(corresponding to an ~10-cm jump)	—	—	—	—	—	—
						—	—	—	—	—	—
Fessl et al[19]	Free weights	Interday	Computation-based method	SJ[a]	0% to 80% BM	—	—	—	—	~2.1% to 4.4%	~.97 to .99
				SJ[b]		—	—	—	—	~3.0% to 8.3%	~.77 to .93
Valenzuela et al[3]	Free weights	Interday	Computation-based method	SJ	0% to 70% BM	± ~1 to 3	—	—	~0.65 to 2.42	~3.8% to 7.8%	~.69 to .96
	Smith machine						—	—	~0.71 to 2.42	~4.4% to 7.8%	~.85 to .96
Lindberg et al[2]	Free weights	Interday	Force plate	SJ	0.5 to 80 kg (or 80% BM)	~2 to 4	5% to 10%	—	1.20	6.8%	—
	Free weights			CMJ							—
Kotani et al[4]	Free weights	Interday	Force plate	SJ	0% to 100% BM	—	—	—	~3.5	~10%	—

Abbreviations: BM, body mass; CMJ, countermovement jump; CV, coefficient of variation derived from SEM (in % of mean values); h_{po}, range of motion; ICC, intraclass coefficient; SEM, standard error of measurement (in raw units); SJ, squat jump.

[a] Task-experienced participants. [b] Task-inexperienced participants.

Table 2 Force–Velocity Relationship Quality and Reliability of “Output” Variables in Previous Studies

		FV relationship, r^2	P_{max}			F_0			v_0			S_{Fv}		
		Median/mean (SD)/range	SEM	CV, %	ICC	SEM	CV, %	ICC	SEM, m/s	CV, %	ICC	SEM, N·s/m	CV, %	ICC
Cuk et al[8]	Force plate—SJ	0.919	86 W	5.4	.93	127 N	5	.95	0.55	6.0	.93	82	9.8	.96
	Force plate—CMJ	0.987	59 W	2.4	.98	80 N	3	.98	0.11	3.3	.96	52	5.7	.98
Garcia-Ramos et al[13]	Free weights—SJ	0.988	54 W	3.8	.93	164 N	6.7	.82	0.16	6.4	.84	135	12.6	.81
	Smith machine—SJ	0.960	60 W	4.2	.91	211 N	7.6	.75	0.16	7.5	.85	192	14.0	.82
	Free weights—CMJ	0.996	51 W	2.4	.97	83 N	3.4	.88	0.17	4.9	.81	57	8.2	.69
	Smith machine—CMJ	0.994	95 W	4.5	.90	99 N	3.9	.88	0.22	6.5	.79	78	9.9	.79
Jimenez-Reyes et al[16]	Force plate—CMJ	—	—	—	—	—	—	—	—	—	—	—	—	—
	Computation method—CMJ	—	—	5.5	.98	—	1.2	.99	—	7.6	.98	—	4.8	.99
Janicijevic et al[15]	Force plate—90° knee	0.976	52.9 W	3.8	.96	89.9 N	3.7	.95	0.161	7.0	.85	103	9.3	.90
	Force plate—pref. knee angle	0.986	66.5 W	4.2	.96	148.7 N	5.7	.88	0.242	9.9	.68	162	14.7	.69
	Computation method—90° knee	0.994	52.3 W	3.3	.96	71 N	2.9	.96	0.156	6.1	.77	82	8.4	.86
	Computation method—pref. knee angle	0.990	52.8 W	3.2	.97	110 N	4.3	.93	0.177	7.0	.80	112	10.7	.79
Fessl et al[19]	Computation method—90° knee	$\geq 0.95^a$	—	3.1	.98		1.9	.91		4.0	.95	—	6.2	.86
		$\geq 0.95^b$	—	5.1	.78		3.9	.89		7.9	.70	—	10.9	.83
Valenzuela et al[3]	Free weights—SJ	0.96 (0.04)	7.75 W/kg	30.0	.38	3.0 W/kg	9.9	.04	1.36	34.5	.07	—	42.1	−.30
	Smith machine—SJ	0.97 (0.03)	3.47 W/kg	11.0	.75	1.0 N/kg	3.4	.95	0.57	12.6	.77	—	12.1	.84
Lindberg et al[2]	Force plate—SJ	0.95–1.00	—	~9.7	~.84		~9	~.76		~16	~.57	—	~26	~.54
	Force plate—CMJ	0.95–1.00	—	~9.8	~.75		~7	~.85		~16.5	~.32	—	~23.5	~.45
Kotani et al[4]	Force plate—SJ	—	CV ~ 24.5% and ICC ~ .48											

Abbreviations: CMJ, countermovement jump; CV, coefficient of variation derived from SEM (in % of mean values); F_0, maximal theoretical force; h_{po}, range of motion, ICC, intraclass coefficient; P_{max}, maximal power output; SEM, standard error of measurement (in raw units); S_{Fv}, slope of the Fv relationship; SJ, squat jump; v_0, maximal theoretical velocity.

[a]Task-experienced participants. [b]Task-inexperienced participants.

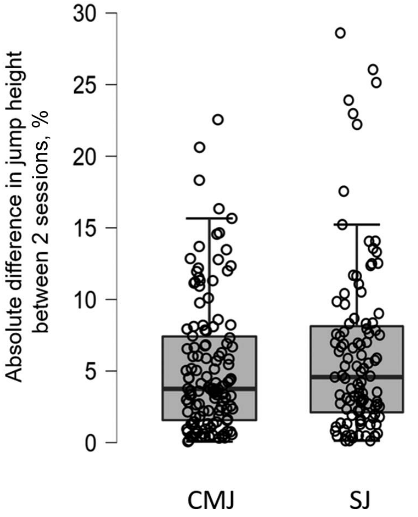

Figure 1 — Absolute differences in jump height between 2 testing sessions separated by 1 week for CMJ and SJ, adapted from available data of Lindberg et al.[2] Circles represent individual values, and box plots represent minimum value, 25th quartile, median value, 75th quartile, and maximum value. Maximum and minimum values do not account for outliers, which correspond to circles above the minimum–maximum range. CMJ indicates countermovement jumps; SJ, squat jumps.

second test.[14,18,24] Simulated athletes presenting an Fv relationship with $r^2 < .95$ were removed, this liberal threshold corresponding to typical experimental guidelines.

The simulations showed that linear fit quality of the Fv regression decreased when variability in h and h_{po} increased: h_{po} and h variability < ~4% to 5% seems acceptable to guarantee well-fitted Fv relationships, with only <10% of Fv relationships classified as first glance as unacceptable (ie, $r^2 < .95$, Figure 2G, 2H, and 2I). Once the nonacceptable Fv relationships were removed, the simulations showed that when aiming to estimate FvP outputs with typical error <10% (ie, a common threshold in sport science), the noise in h_{po} and h must be < ~4% to 5% (ie, both ~1 to 1.2 cm; Figures 2 and 3). Unsurprisingly, h and h_{po} variability in the 3 aforementioned studies is clearly higher than these theoretical thresholds. Consequently, inflated variability in output variables is partly caused by input variabilities that are too high to infer FvP variables, and not only by the FvP profile concept in jumping and the associated method, per se. The recent study of Fessl et al[19] provides practical support to these simulation results, with less task-habituated athletes presenting greater variability in both h and FvP variables. Specifically, ski-jumping athletes, exhibiting variability in h <4.5% across different loads, presented variability in FvP variables <6.5%, and unexperienced sports students, exhibiting 3.0% to 8.3% variability in h, presented variability in FvP variables from 3.9% to 10.9% (Tables 1 and 2). Importantly, errors that would be otherwise acceptable when examining h in isolation can directly contribute to unacceptable error rates extrapolating FvP variables.

Relevance of Concepts, Validity of Methods, or Reliability of Measurements

More generally, the distinction between insufficient reliability in data measurements, validity of models or testing methods, and relevance of biomechanical and physiological concepts can be discussed whatever the physical qualities evaluated. For example, the earlier observations for FvP in jumping apply to sprint running[12,25]: Should split times or instantaneous velocity be measured unreliably, FvP output variables will be similarly unreliable, and vice versa. In the same manner, VO_2max will appear unreliable with unreliable gas exchange measurements (eg, uncalibrated machine, athletes not presenting maximal effort, or other imprecise testing procedures), yet it would be misleading to conclude that the concept of VO_2max itself is unreliable or flawed and subsequently broadly caution its use for athletic testing. Nevertheless, it is worth noting that the biological and technical/random variability is greater for mechanical outputs of the neuromuscular system estimated from different measurements performed in several conditions compared with kinematic data characterizing the task configuration and the effort performed by the athletes in each isolated condition—which, in this example, corresponds to FvP variables h_{po} and h, respectively. Moreover, whatever the methods used to determine the FvP relationship (eg, kinetic or kinematic measurements, dynamics or inverse dynamics approaches), greater variability is observed in force/acceleration data versus velocity/position data. However, despite often inevitable error inflation, kinetic data characterizing force production capacities of the neuromuscular system allow a more detailed exploration of factors underlying performance than kinematic data alone. Consequently, the interest of such approaches is in balancing the value brought from insight and error magnification. Although, in comparison with jump height alone, the interest of FvP relationship variables has been supported for comparing athletes' force production capacities or for training individualization,[26] experimenters should, nonetheless, be cautious about variability in input measurements. If not, the potential gain in information will be overpassed by the magnified error, as this seems to be the case in the different studies that concluded that FvP relationships are unreliable *in general*.[2–4] The problem is not the FvP relationships themselves or the methods used but an unfavorable balance between measurement variabilities and levels of insight targeted.

Practical Applications

Before challenging concepts, approaches, models, or methods, balanced recommendations should list all sources of measurement uncertainty and provide suggestions to improve subsequent interventions. For FvP testing in jumping, noise can be reduced by averaging several trials per loading condition or considering best values among several trials, increasing the velocity range explored and the number of the experimental conditions used to draw the Fv relationship, using live feedback during testing to control the quality (r^2) of the Fv relationship and redo incorrect trials (eg, by examining points with large residuals, notably if $r^2 < .95$), following a warm-up that includes the range of loads to be used during measurement, and thoroughly standardizing starting position (eg, elastic bands or hard supports). More importantly, all participants must be thoroughly accustomed with maximal intent loaded jumps[19] and follow stringent technical criteria (eg, no countermovement during squat jump, vertical motion only and landing with fully extended lower limbs when using flight time) to validate each trial. External encouragement should be maintained to ensure maximal effort while ensuring the number of trials/loads to not induce fatigue. When these different methodological considerations are scrupulously respected, h reliability of 2% to 5% within or between sessions can be observed[19,27–30] as well as acceptable reliability in FvP variables.[8,13,15,19]

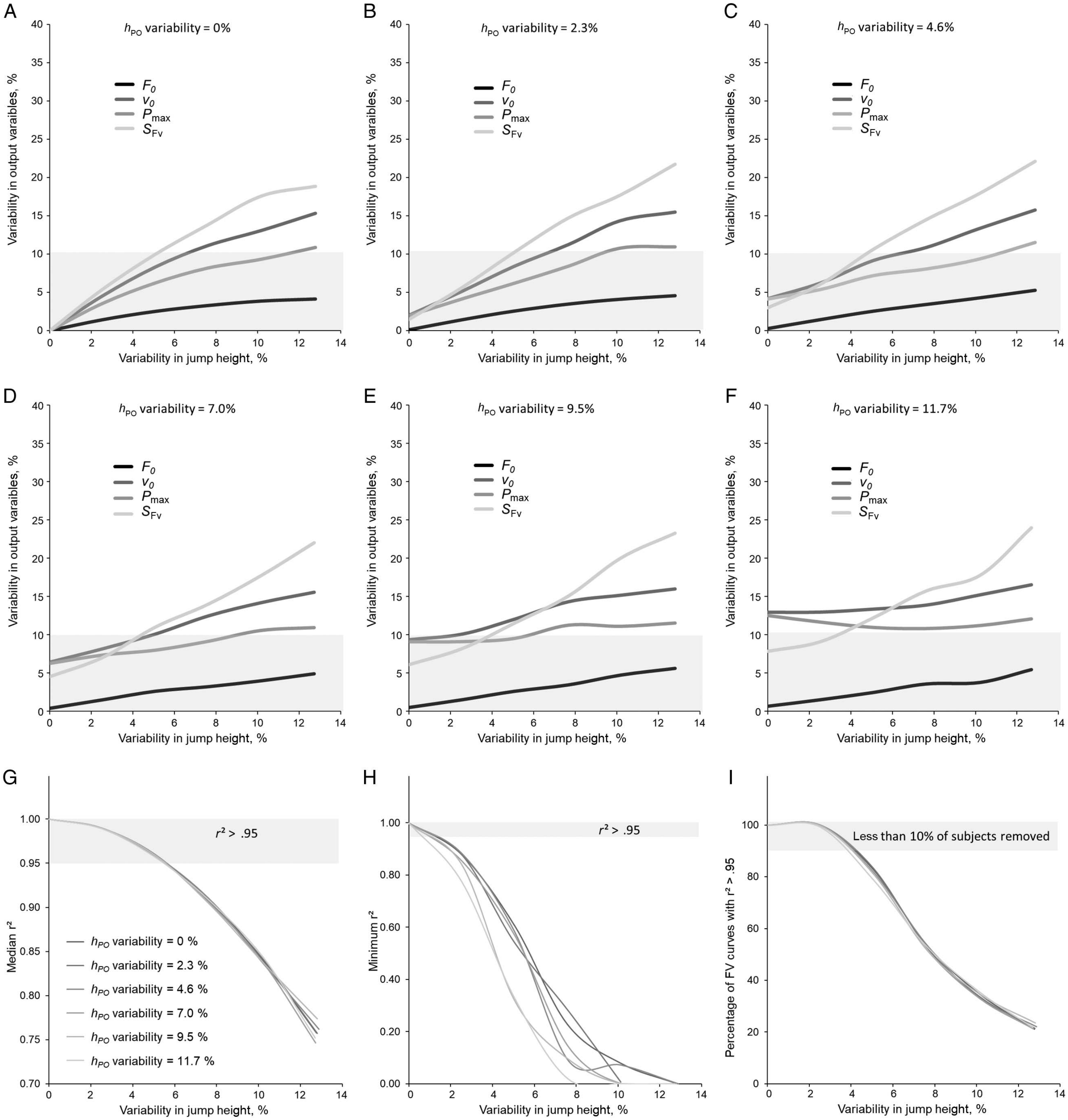

Figure 2 — Random errors in F_0, v_0, P_{max}, and Fv slope (S_{Fv}) according to the variability of jump-height measurement for 6 variability levels of h_{po} (A, B, C, D, E, and F). These random errors were obtained from theoretical simulations based on 3000 virtual subjects (with F_0 ranging between 20 and 40 N/kg, v_0 between 2 and 6 m/s, P_{max} between 16 and 50 W/kg, and h_{po} between 0.25 and 0.45 m) performing 2 Fv jump tests with 5 loads (0%, 25%, 50%, 75%, and 100% BM). The median and minimum r^2 values of theFv relationships obtained across the 3000 subjects, as well as the percentage of subjects presenting an Fv curve r^2 >.95, are presented in G, H, and I.

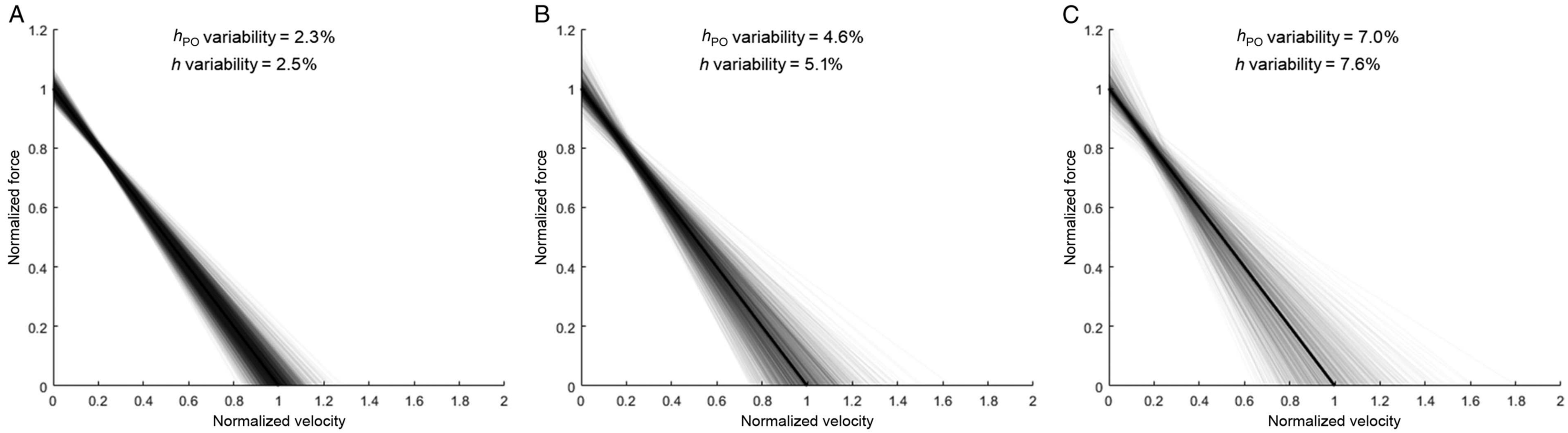

Figure 3 — The Fv relationships from trial 2 (gray) normalized to trial 1 (black) for the 3000 virtual subjects (except subjects with r^2 <.95) for 3 variability levels in h_{po} and h (A: acceptable, B: high, and C: very high). Fv indicates force–velocity; h, height; h_{po}, range of motion.

Some validated field methods do not require costly lab devices or complex data processing and can be easily applied out of the laboratory. However, these "simple" methods cannot escape the influence of biological variability, measurement noise, methodological differences in testing conditions, or unfamiliar subjects. Regardless of the perceived method simplicity, testing requires rigorous setting of procedures, timing (eg, day, week, month, season), and athlete and operator familiarization. These requirements are even more notable when determining integrative indexes based on several measurements, conditions, or model assumptions. Otherwise, the outputs will, at best, lack utility for practice and, at worst, risk being misleading or counterproductive for health, performance, and science. In other words, whatever the cooking method, it is impossible to create a tasty dish from spoiled ingredients.

Conclusion

Overlooking potential sources of error is an ever-present risk in reliability research. Unfortunately, the conclusions of several recent articles assessing the reliability of FvP relationship testing seem to focus almost exclusively on the basic concepts themselves and not on the measurements and model input reliability. Like many neuromuscular or physiological profiling methods, the FvP relationship, based on different measurements in several conditions, is unreliable when the input measurements (notably jumping impulse/height) are imprecise or when the testing conditions are not standardized sufficiently (eg, push-off distance, participants' familiarization with testing conditions)—independent from the method used. As mechanical outputs of the neuromuscular system are estimated from different measurements and conditions, the measurement inaccuracies are magnified in FvP profiling. Consequently, extra caution is required to ensure precise data acquisition and accordingly acceptable output data. Finally, "simple" field-based measures and lab methods require the same methodological rigor, which does not imply that field testing is simple. Simple does not mean easy.

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