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Investigating Vertical and Horizontal Force-Velocity Profiles in Club-Level Field Hockey Athletes: Do Mechanical Characteristics Transfer Between Orientation of Movement?

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ABSTRACT

To inform physical preparation strategies in field hockey athletes, this cross-sectional study investigated the transfer of mechanical characteristics in different force-vectors and determined the correlations between vertical and horizontal force-velocity (F-v) profiles and performance outcomes (i.e., jump height, sprint time). Thirty-one club-level field hockey athletes (age: 23.1 ± 4.3yrs, body mass: 70.6 ± 10.3kg, height: 1.72 ± 0.09m) performed vertical force-velocity profiles by completing countermovement jumps at three incremental loads (bodymass[BM], BM+25% externally added mass relative to BM, BM+50% externally added mass relative to BM), and horizontal force-velocity profiles by performing maximal 30-meter sprint efforts. When comparing matched mechanical variables between F-v profiles in each force orientation, small to moderate significant correlations r = (0.37–0.62, $p \le 0.03$) were observed for relative theoretical maximal force (F_0), power (P_{MAX}) and theoretical maximal velocity (v_0). The performance outcomes of both F-v profiles highlighted a large, significant negative correlation (r = -0.86, p = 0.001) between variables. Multiple linear regression analysis of F-v profiles identified F_0 and v_0 accounted for 74% and 94% of the variability in jump height and sprint time respectively; however, v_0 appeared to be a greater predictor of both performance outcomes. Due to the significant relationships between variables, the results of this study suggest vertical and horizontal F-v profiling may explain the same key lower-limb mechanical characteristics, despite the orientation of the movement task. With club-level field hockey athletes, coaches could potentially use mechanical profiling methods interchangeably to prescribe physical preparation interventions, however for greater neuromuscular and mechanical insight, it is likely worthwhile to assess mechanical strengths and weaknesses in both force-vectors.

Keywords: force, velocity, power, transfer, mechanical, field hockey

INTRODUCTION

Field hockey is a team-based sport which relies on skills, team tactics and strategy but also has strong requirements of high-intensity movement demands [1]. In elite men's and women's field hockey, typical distances covered during high-velocity and high-acceleration efforts are approximately 10–20-meters thereby relying on the player to express their lower body mechanical characteristics including force, velocity, and power [1-3]. One neuromuscular diagnostic assessment which can be utilized to describe mechanical limits of the neuromuscular system in jumping and sprinting actions is known as force-velocity (F-v) profiling. Despite typical team sport strength, power and fitness test batteries providing quantitative outcome measures of performance (i.e., jump height and sprint time)[4], these fail to explain the underpinning characteristics contributing to performance. Whereas force-velocity profiling models and describes mechanical characteristics across the entire force-velocity continuum thereby providing practitioners with actionable data to inform on and on and off-field training interventions. To date, most studies in field hockey have relied on time-motion analysis (i.e., global positioning systems) to quantify different physiological demands during competition in an attempt to prepare players for match demands [1,5-8], however, there is limited information about mechanical characteristics required in the sport and how this information could be utilized to inform monitoring and physical preparation strategies [9].

Mechanical profiling in other team sports including soccer and netball have described the underpinning mechanical characteristics of jump (i.e., vertical force vector) and sprint performance (i.e., horizontal force vector), using the same three key variables; theoretical maximal force (F_0), theoretical maximal velocity (v_0), and theoretical maximal external power (P_{MAX}), plus the performance outcome (i.e., jump height and sprint time). These variables describe the F-v and power-velocity (P-v) relationships of each action. Vertical F-v profiles determine jump-specific mechanical characteristics of the propulsive phase of a loaded or unloaded countermovement or squat jump [10] from the inverse dynamics of the centre of mass [11] or ground reaction force (GRF) using force plates [12], while horizontal F-v profiles provide sprint-based mechanical characteristics derived from modelled velocity-time (or position-time) data of maximal effort sprint accelerations using inverse dynamics [13]. Furthermore, analyzing the mechanical relationships which exist between actions in field hockey players would therefore identify a level of *mechanical transfer*.

When exploring mechanical transfer (i.e., matched variables between each action [vertical/horizontal directed force production]) between vertical and horizontal based actions in amateur, national and elite level team sports [14-17], research has demonstrated maximal external power showed the strongest significant relationship (r = 0.40–0.75, $p \leq 0.04$) between jumping and sprinting actions [14,18-21], however this is yet to be explored in field hockey. Despite strong associations with external maximal power, force (r =-0.12–0.58) and velocity (r =-0.31–0.71) demonstrated trivial to moderate, and often non-significant mechanical transfer between actions, potentially highlighting greater independent neuromuscular and physiological characteristics of these two variables [22]. Previous research studies [16,18,20] suggested the performance level of the athlete, training and chronological age, homogeneity of participants, sport and position influenced the mechanical relationships between matched variables, but a consensus was not reached on the *transference of training effect* [23]. In addition, it is of interest to strength and conditioning coaches to understand, (1) whether both vertical and horizontal F-v profiling assessments are necessary to understand the current mechanical characteristics of the athlete, and (2) whether mechanical characteristics are independent of orientation of force and therefore require specific physical preparation training interventions to improve neuromuscular output.

Training studies investigating the development and transfer of strength and power adaptations between exercise types have typically focused on vertical force and power production and sprint performance [17,24-28]. The rationale for using exercises oriented vertically (i.e., loaded jumps) to improve performance in exercises oriented horizontally (i.e., sprinting) assumes that improvement in absolute GRF production will positively transfer between both actions. For example, significant negative correlations in team sport and sprint athletes have been reported for relative squat strength and sprint times between 5-60 meters ($r \geq$ -0.55) [28,29], while the level of one repetition-maximum (1-RM) in the back squat relative to body mass correlated strongly with lower sprint time (<36.6m) and increased vertical jump height ($r \geq$ 0.78)[30,31]. Barr et al. [27] also reported greater levels of strength in one repetition maximum power clean and front squat positively influenced sprint kinematics (r = 0.70, d=

0.6–0.81) in elite rugby players. Despite evidence identifying relationships between force production and performance outcomes in the vertical and horizontal orientation, the underpinning mechanical determinants of performance in each orientation must be considered. Vertical impulse (force*time) is the primary variable influencing take-off velocity and therefore jump height [32], whereas in sprinting, the athlete's mechanical effectiveness to produce and apply a greater ratio of antero-posterior GRF, compared to total GRF, across each ground contact as running velocity increases limits sprint performance [33]. Furthermore, since mechanical and technical differences in force application exist between both actions, transfer of characteristics should be limited and therefore oppose the force-vector theory [34].

The force-vector theory states that sports skills can be classified based on the direction of force expression relative to the global (world fixed) coordinate frame [34-37]. In this regard, jumping actions would be classified as a vertical movement activity and sprint actions a horizontal movement activity. Despite this, the expression of force between vertical and horizontal actions has been described as similar relative to the local coordinate system of the athlete [34], where both actions rely on lower limb triple extension yet with different muscle recruitment patterns (i.e. knee dominant [quadriceps] vs hip dominant [hip extensors]). Therefore, according to the theory, vertical force expression during a back squat will show greater neuromuscular transfer in unloaded movements such as a vertical jump, yet limited transfer to a horizontal-based movements such as a maximal sprint effort i.e., dynamic correspondence [38]. Consequently, this would infer matched mechanical characteristics would show low associations due to the technical application of force into the ground i.e., expressing force vertically versus expressing force horizontally [39].

Therefore, the aim of this study was twofold. First, we analyzed the relationships and mechanical transfer of characteristics in jumping and sprinting actions using force-velocity profiling methodology in field hockey athletes. Second, the aim was to analyse the influence of force and velocity, as predictor variables for explaining variability in jump and sprint performance (i.e., jump height, 30m sprint time) from both force-velocity profiles. It was hypothesized that (a) limited transfer would exist between mechanical variables and performance outcomes in vertical and horizontal F-v profiles due to the specificity of the movement task [15,40] thereby adhering to the force-vector theory, and (b) multiple linear regression models should provide similar prediction values to explain variability in performance, as they are based on the same characteristics of the neuromuscular system. The results of this study are expected to inform practitioners working with club-level field hockey athletes about the most appropriate mechanical profiling methodology to inform physical preparation strategies and potentially influence exercise selection to improve jump and sprint performance, plus may also provide neuromuscular reference data for field hockey athletes.

METHODS

Subjects

A power analysis was conducted prior to the study (G*Power 3)[41] using the following test details: 'Correlation: bivariate normal model', an effect size of 0.5, alpha of 0.05 and power of 0.8 [42], which suggested the total sample size of the study should include 29 subjects. Thirty-one club-level field hockey athletes (male n=15: 23.2 ± 4.7 years, body mass 75.6 ± 8.2 kg, and height 1.79 ± 0.06 m; female n=16: 23.1 ± 4.0 years, body mass 64.7 ± 7.6 kg, and height 1.65 ± 0.06 m) volunteered to participate and provided their written informed consent before beginning the study. Inclusion criteria included: subjects involved in club-level sport; a background in resistance training of greater than 12 months; and aged 15-35 years. Exclusion criteria maintained that subjects needed to be six-months free of musculoskeletal injuries which may prevent them performing maximal effort jump squats or maximal effort sprints. If under 18 years of age (males[n=2], female [n=1], the adult guardian acknowledged the participants experience with jumping and sprinting actions and provided written informed consent before beginning the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Social and Behavioural Research Ethics Committee at Flinders University (Ethics App Number: 8146).

Experimental Design

This investigation was a cross-sectional study design focussed on the transfer of mechanical characteristics between vertical and horizontal force-velocity profiles in club-level field hockey athletes. The familiarization period occurred during the pre-season period when participants were engaged in two training sessions per week (1 x on-field hockey session, 1 x running-based conditioning). Gym-based and sprint-based familiarization session were performed with the subjects two weeks prior to the testing date and led by the primary investigator, specifically focussing on jump squats using a hexbar across key loading parameters and maximal effort sprinting over distances between 10-30 meters. as these would be the testing methods for the vertical and horizontal F-v profiles respectively. The environmental conditions observed on the day of testing included: Temperature (min 21.5°C, max 33.0°C, SE winds 13km/h, 1017.5hPA. Vertical F-v profiling was performed approximately 60 minutes prior to horizontal F-v profiling. Testing was performed in this order to limit fatigue when completing sprint efforts.

Testing procedures

Vertical force-velocity profiling

A warmup consisting of three minutes of metronome paced step-ups, dynamic movements plus a series of sub-maximal and maximal effort countermovement jumps were completed prior to the jumping protocol. All subjects then completed three maximal effort jump trials at three incremental loading conditions; body mass (BM) (LO1), 25% externally added mass relative to BM (LO2) and 50% externally added mass relative to BM (LO3). This approach to force-velocity profiling was selected as this has been shown to provide reliable and valid data when compared to a multiple point (5-9 loads) approach [10]. Upon landing for all loading conditions, subjects were asked to touch down with the same leg position as when they took off, (i.e., with an extended leg and maximal foot plantar flexion). If all requirements were not met, the trial was repeated. During all trials, the research staff made an effort to ensure maximal intent by providing subjects with internal and external verbal cues such as “squat to your preferred depth then rapidly extend your hips, knees and ankles” [43] and “jump towards the ceiling” [44]. A two minute of recovery period was taken between trials and 4–5 minute recovery period between different loads [45]. Countermovement jump (CMJ) trials were performed using the high handles of a 15kg free-weight hex bar (or purpose-built polyvinyl chloride [PVC] hexagon equivalent) with subjects standing upright holding the bar off the ground prior to descending into the countermovement jump. Arms remained extended during all CMJ trials. Subjects self-selected the countermovement depth and were not constrained by a box or band, to encourage individual jump strategy [46].

To measure vertical ground reaction force (GRF) data, jump trials were conducted with the subject standing with each foot on a separate portable force plate system levelled on a concrete floor (35cm by 35cm, PASPORT force plate, PS-2141, PASCO Scientific, California, USA). This model of portable force plate has previously been validated and deemed reliable against in-ground laboratory grade force plates [47]. Before initiating the jump action, subjects were required to stand stationary at full stature for at least 1-second with their left and right foot on the centre of each force plate, to ensure the weighing phase could be calculated accurately [43]. Identification of vertical jump take-off and touch-down was determined using a threshold of vertical ground reaction force equal to 5 times the standard deviation of flight force (i.e., when the force plate was completely unloaded)[43]. Movement prior to the initiation of the jump would void the trial and the jump would be repeated. Prior to the next trial, the force plates were zeroed. Vertical GRF was continuously sampled at 1000 Hz for each force plate, with vertical force (Fz)-time data being stored within a local computer.

To determine the jump force-velocity profile, mean values of force and velocity were determined using unfiltered ground reaction force-time data during the concentric portion of the countermovement jump. Key phases of the countermovement jump were outlined using the force-time characteristics described by McMahon et al. [43]. The concentric phase was defined as the point at which centre of mass velocity becomes positive and the athlete begins moving vertically from the lowest point of the countermovement until the point of take-off [43]. Mean vertical GRF was calculated by averaging vertical force from the dual force plate system across the time points established for the concentric phase of the jump. The instantaneous vertical velocity across the concentric phase of each jump type was calculated via integration of the centre of mass (COM) vertical acceleration signal over time, via force plate data and then averaged across the concentric phase. Mean system power across the propulsion phase was then determined as the product of mean GRF and estimated mean COM velocity according to the sample rate from both force plates.

Force-velocity variables were established using mean vertical ground reaction force values which were entered into a customised Microsoft Excel spreadsheet as outlined by Garcia-Ramos et al. [48]. At each load, the jump trial which recorded the highest take-off velocity (maximum vertical velocity) was used for statistical analyses, since this likely represents the overall maximal capabilities of the neuromuscular system during the jumping action [49]. A least squares linear regression model was then applied to the mean force and velocity data to determine the F-v relationship variables. Absolute (N) and relative theoretical maximal force ($N.kg^{-1}$) (F_0) and theoretical maximal velocity ($m.s^{-1}$) (v_0) were then established as the intercepts of the linear regression model, while absolute (W) and relative theoretical maximal power ($W.kg^{-1}$) were described by the polynomial power-velocity (P-v) relationship (Figure 1: A). The F-v data achieved across the three loading conditions describes the absolute ($N.s^{-1}.m^{-1}$) and relative ($N. s^{-1}.m^{-1}.kg^{-1}$) slope of the F-v profile (S_{FV}) and is calculated as: $S_{FV} = F_0/v_0$.

Horizontal force-velocity profiling

Sprint testing was performed on an artificial turf surface. The standardized warm-up included 5 minutes of light jogging, dynamic running-based drills (i.e., A-skips, high-knees, scissor bounds) and movements, and 4-8 linear accelerations from 10-40m progressing from sub-maximal to maximal. Following the warmup, subjects performed two 30-metre maximal sprint efforts from a 2-point staggered stance (dominant foot forward) wearing typical athletic footwear. To initiate the start of the sprint effort, subjects were given a verbal countdown of "3, 2, 1, sprint". A 5-minute passive recovery period occurred following each sprint to reduce fatigue prior to the next maximal effort.
The MuscleLab™ is a system which uses an optical laser to measure sprint distance over and time and automatically calculates sprint mechanical properties. During each sprint attempt, speed measurements were recorded continuously using a laser gun (CMP3 Distance Sensor, Noptel Oy, Oulu, Finland), sampling at 2.56 KHz (Figure 2). The laser was positioned 5 m directly behind the starting position and at a vertical height of 1 m to approximately align with the subject's centre of mass. Testing was performed by R.VT who is experienced using this technology. A polynomial on distance over time was fitted, and automatically resampled over 1000Hz by MuscleLab v10.212.98 (Ergotest Technology AS, Langesund, Norway). The in-built software automatically calculates peak velocity ($m.s^{-1}$), the distance at which peak velocity was reached, peak force per body mass ($N.kg^{-1}$), peak power per body mass ($W.kg^{-1}$) and the strength–speed factor (ratio of force and velocity capabilities). Graphical representation of the force-velocity and power-velocity relationships evident in the sprint force-velocity profile is shown in Figure 1: B.

Statistical Analysis

Statistical analyses on all force-velocity data were determined from input into custom built Microsoft Excel spreadsheets [50] plus coded in R (v3.6.1; R Foundation for Statistical Computing, R Core Team, Vienna, Austria), in the RStudio environment (v1.2.519; RStudio, Inc., Boston, MA) using various statistical packages. All descriptive data are presented as mean ± standard deviation (SD) and were assessed and confirmed for normality using the Shapiro-Wilks test. Pearson's product-moment correlation coefficients (*r*) and linear regression models were selected to compare, analyze and determine relationships between matched variables

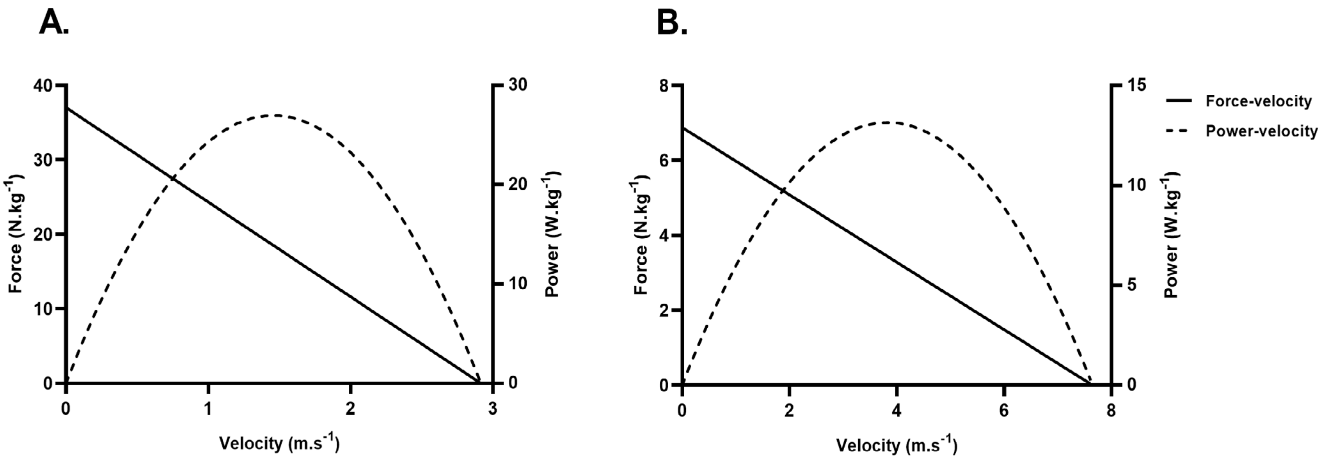

Figure 1. Mean force-velocity and power-velocity characteristics of field hockey athletes obtained during vertical (A) and horizontal (B) force-velocity profiles.


Figure 2. MuscleLab™ is a system which uses an optical laser to measure sprint distance over time and automatically calculates sprint mechanical properties

in both profiling assessments (i.e., vertical, and horizontal). Performance outcomes (i.e., jump height and sprint time) were labelled as dependent variables and then analyzed with multiple linear regression models using F_0 and v_0 as independent variables. Relative maximal power (P_{MAX}) was not used as an independent variable due to its multicollinearity with other variables. Thresholds for evaluation of Pearson's correlation coefficients (*r*) were quantified using the following scale: (0-0.09, trivial; 0.10-0.29, small; 0.30-0.49, moderate; 0.50–0.69. large; 0.70-0.89, very large; ≥0.90, nearly perfect [51]. An alpha value of $p \leq 0.05$ was used to indicate statistical significance.

RESULTS

Descriptive statistics for all variables between force-velocity profiling assessment in each force orientation are highlighted in Table 1. Correlational data and linear regression analysis of theoretical relative maximal force and power and theoretical maximal velocity for each mechanical profile showed moderate to large, significant correlations ($r = 0.38–0.61$, $p \leq 0.03$) between jump and sprint force-velocity variables (Table 1, Figure 3). Trivial, non-significant relationships ($r = 0.06$, $p = 0.72$) were reported for the S_{FV} between profiling assessments. The performance outcome (i.e., jump height, sprint time) in each orientation showed a significantly large, negative correlation with each other ($r = -0.86$, $p \leq 0.01$) (Table 2).

When analyzing mechanical characteristics and performance outcomes, jump height showed moderate to large correlations with relative F_0, v_0 and relative P_{MAX} from the vertical F-v profile ($r = 0.63–0.87$, $p \leq 0.01$). Thirty-meter sprint time showed moderate to large ($r = -0.40– -0.73$, $p \leq 0.01$) negative correlations with relative F_0, v_0 and relative P_{MAX} in the horizontal direction (Table 2, Figure 4). Moderate to large significant correlations were also reported for performance outcomes using the mechanical variables from the opposite F-v profile (Table 2, Figure 4) (i.e., relationship between vertical variables and horizontal performance outcome and vice versa). Relative F_0, P_{MAX} and v_0 in the horizontal direction were significantly correlated with jump height ($r = 0.59–0.89$, $p \leq 0.001$), whereas F_0, P_{MAX} and v_0 in the vertical direction were also significantly correlated with 30-meter sprint time ($r = -0.75– -0.94$, $p \leq 0.001$). The slope of the F-v profile in both orientations showed trivial, non-significant relationships with the performance outcomes ($r = -0.003 –0.01$, $p \geq 0.95$).

Multiple linear regression models for prediction of the performance outcome from each F-v profile identified F_0 and v_0 accounted for 74% and 94% of the variability of jump height and sprint time respectively (Table 3). Both mechanical variables were deemed significant predictors of performance outcomes when modeling jump height and sprint time. Specifically, we found the regression model for the vertical F-v profile predicted v_0 would increase jump height (0.12cm) to a greater degree compared to F_0 (0.009cm). Similarly, multiple regression model for prediction of sprint time identified v_0 (-0.40sec) explained greater sprint performance variability than F_0 (-0.11sec).

DISCUSSION

The purpose of this cross-sectional study was to investigate the transfer of mechanical characteristics between vertical and horizontal force-velocity profiles, analyze force-velocity variables to explain variability in jump and sprint performance and potentially provide some reference data for field hockey practitioners using mechanical profiling as part of their neuromuscular assessments. Despite various studies providing insight to the intensity of running demands during competition field hockey [1,2], to the best of our knowledge, this is the first study to analyze mechanical profiling within a field hock-

Table 1. Descriptive statistics of mechanical variables from vertical and horizontal force-velocity profiles.

Variables	Abbreviation	Action	Mean ± SD	*r* (95% CI)	*p*
Relative maximal force ($N.kg^{-1}$)	F_0	Jump	37.02 ± 5.31	0.37 (0.02, 0.64)	0.03*
		Sprint	6.88 ± 1.05		
Theoretical maximal velocity ($m.s^{-1}$)	v_0	Jump	2.97 ± 0.41	0.47 (0.14, 0.70)	≤ 0.01*
		Sprint	7.69 ± 0.78		
Relative maximal power ($W.kg^{-1}$)	P_{MAX}	Jump	27.59 ± 5.92	0.62 (0.32, 0.79)	≤ 0.01*
		Sprint	13.19 ± 3.28		
Relative force-velocity slope ($N.s^{-1}.m^{-1}.kg^{-1}$)	S_{FV}	Jump	-12.70 ± 2.78	0.06 (-0.29, 0.41)	0.72
		Sprint	0.90 ± 0.10		
Performance outcome (i.e., jump height, sprint time)	metre	Jump	0.32 ± 0.08	-0.86 (-0.92, -0.72)	≤ 0.01*
	sec	Sprint	4.68 ± 0.41		

*CI = confidence interval. * = p ≤ 0.05*

Table 2. Correlation coefficient data between mechanical characteristics and performance outcomes from vertical and horizontal force-velocity profiles.

Variable	Jump Height (m)	
	r	*p*
VTC F_0 ($N.kg^{-1}$)	0.63	≤ 0.001*
VTC v_0 (m.s-1)	0.62	≤ 0.001*
VTC P_{MAX} ($W.kg^{-1}$)	0.87	≤ 0.001*
VTC S_{FV}	-0.003	0.98
HZT F_0 ($N.kg^{-1}$)	0.59	≤ 0.001*
HZT v_0 ($m.s^{-1}$)	0.89	≤ 0.001*
HZT P_{MAX} ($W.kg^{-1}$)	0.77	≤ 0.001*
HZT S_{FV}	-0.04	0.81

Variable	Sprint Time (sec)	
	r	*p*
VTC F_0 ($N.kg^{-1}$)	-0.75	≤ 0.001*
VTC v_0 ($m.s^{-1}$)	-0.94	≤ 0.001*
VTC P_{MAX} ($W.kg^{-1}$)	-0.88	≤ 0.001*
VTC S_{FV}	0.03	0.84
HZT F_0 ($N.kg^{-1}$)	-0.62	≤ 0.001*
HZT v_0 ($m.s^{-1}$)	-0.40	0.02*
HZT P_{MAX} ($W.kg^{-1}$)	-0.73	≤ 0.00*1
HZT S_{FV}	0.01	0.95

*VTC = vertical, HZT = horizontal, * = p ≤ 0.05*

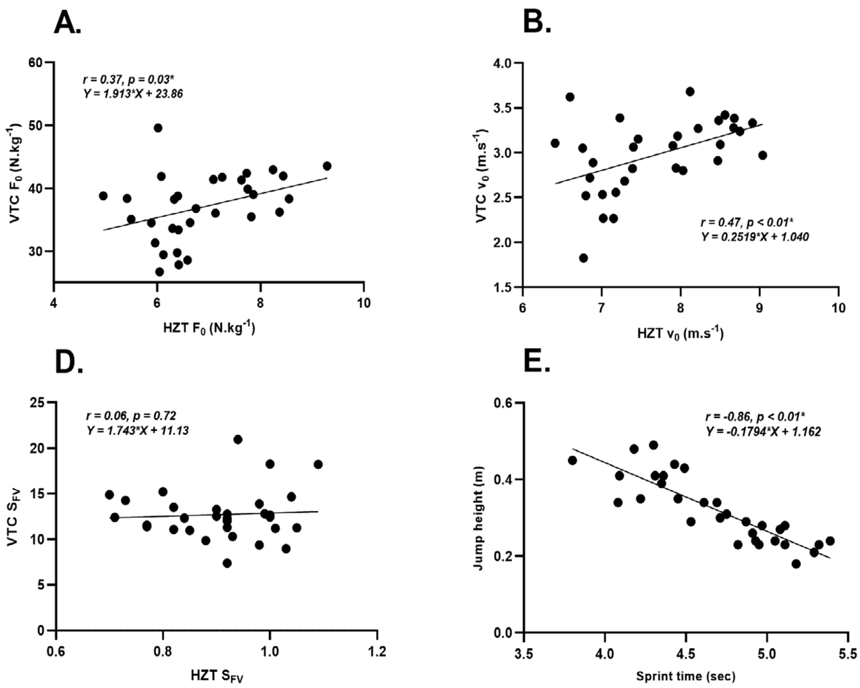

Figure 3. Linear regression models showing the relationships between matched mechanical variables across vertical and horizontal force-velocity profiles. A: Relative maximal force; B: Theoretical maximal velocity; C: Relative maximal power; D: Slope of the force-velocity profile; E: Performance outcome for each profile. VTC = vertical, HZT = horizontal.

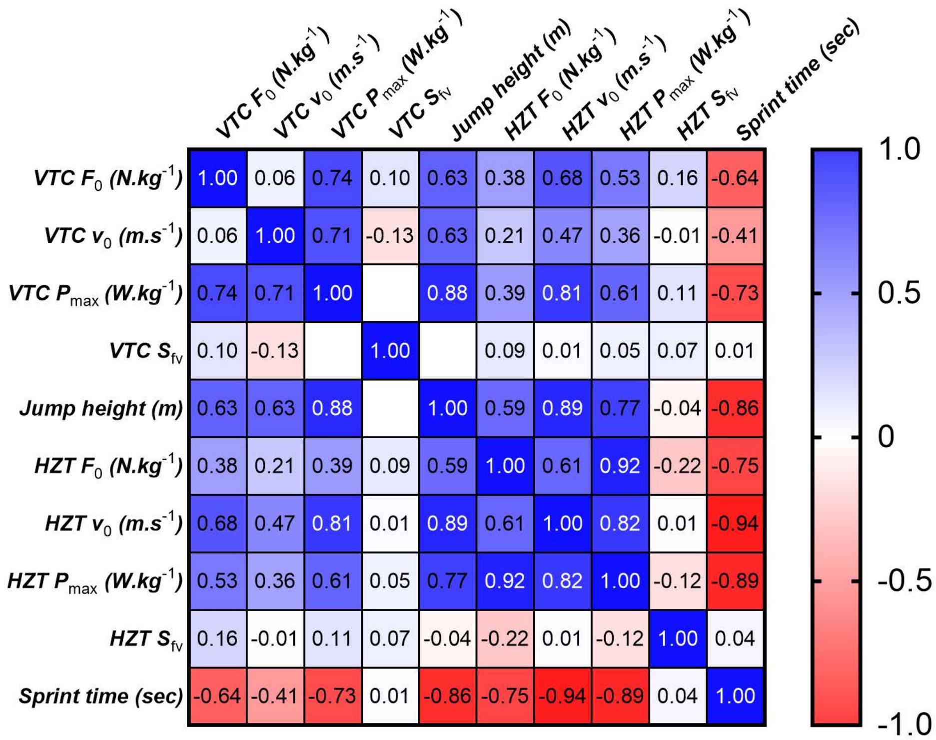

Figure 4. Correlation matrices of vertical and horizontal force-velocity variables. VTC = vertical, HZT = horizontal.

Table 3. Multiple linear regression analysis of performance outcome predictor variables from vertical and horizontal force-velocity profiles.

	Jump height (m)					
Variable	**R^2**	**Coefficient**	**Standard error**	**95% CI**	**t**	***p***
	0.74					
Intercept		-0.40	0.08	-0.56, -0.24	5.04	<0.0001**
VTC F_0 (N.kg^{-1})		0.009	0.001	0.006, 0.01	6.27	<0.0001**
VTC v_0 (m.s^{-1})		0.12	0.02	0.08, 0.16	6.21	<0.0001**
	Sprint time (sec)					
Variable	**R^2**	**Coefficient**	**Standard error**	**95% CI**	**t**	***p***
	0.94					
Intercept		8.58	0.18	8.20, 8.96	45.78	<0.0001**
HZT F_0 (N.kg^{-1})		-0.11	0.02	-0.16, -0.06	5.02	<0.0001**
HZT v_0 (m.s^{-1})		-0.40	0.03	-0.46, -0.34	13.30	<0.0001**

*VTC = vertical, HZT = horizontal, CI = confidence interval, * p ≤0.05, ** p≤0.01*

ey context. We believe the information presented about mechanical profiling in different force orientations suggests within a context of club-level field hockey players, this information can provide strong utility for sports practitioners when developing physical preparation strategies across the field hockey season.

Our key findings are as follows: (a) when comparing matched mechanical characteristics, significant moderate to large relationships are evident between vertical and horizontal mechanical profiles, (b) the performance outcomes (i.e., jump height and sprint time) showed moderate to very large (positive and negative) significant relationships with mechanical variables in both the vertical and horizontal orientation, and (c) furthermore, v_0 showed greater utility in explaining the variability in jump and sprint performance compared to F_0. Therefore, vertical and horizontal force-velocity profiles present similar mechanical characteristics and can potentially can infer performance outomes in each force orientation.

In reference to our first hypothesis, we identified matched mechanical characteristics including force, velocity and power demonstrated significant relationships between vertical and horizontal F-v profiles, thereby highlighting a strong *transference effect*. This contradicted our initial hypothesis and previous studies in other team and individual sports [16,18,20] which identified limited transfer between matched mechanical characteristics in jump and sprint actions, specifically for F_0 and v_0. Related research on multi-sport athletes (n=553) [16] reported trivial to large (positive and negative) correlation coefficients for F_0: $-0.12 \le r \ge 0.58$; v_0: $-0.31 \le r \ge 0.71$; P_{MAX}: $-0.10 \le r \ge 0.67$; and performance outcomes: $-0.92 \le r \ge -0.23$, however no consensus was reached to explain trivial or strong associations or lack of significance between mechanical characteristics. Despite not being confirmed, it has been has proposed the transfer of mechanical qualities is greater for athletes of lower ability levels [16] suggesting training absolute force qualities would positively influence neuromuscular output in all force orientations, which opposes the force-vector theory. At a lower 'training age', the trainability of the athlete is potentially higher therefore non-specific training methods may have greater impact on performance [16]. Furthermore, previous studies focussed on the transfer of mechanical qualities between horizontal and vertical actions have also suggested, gender, bodymass, lower limb neuromuscular properties (i.e., intramuscular coordination) and resistance training background may influence the correlation between variables [17,23,26,27], which may be the case in this study. Therefore, for club-level field hockey athletes. these findings highlight physical preparation strategies including exercise selection should likely span the force-velocity continuum using exercises oriented both vertically and horizontally, regardless the targeted movement pattern [33].

Without identifying results within a field hockey context, an analysis of matched mechanical characteristics across a range of individual and team sports suggests the cohort within this study (Table 1) have similar mechanical and performance characteristics in vertical and horizontal F-v profiles as medium level/semi-professional soccer players and low-level sport science students (i.e. amateur) respectively (vertical [VTC] F_0: 31.8N.kg^{-1}, horizontal [HZT] F_0:

6.45N.kg^{-1}; VTC v_0: 2.88m.s^{-1}, HZT v_0: 7.60m.s^{-1}; VTC P_{MAX}: 22.8W.kg^{-1}, HZT P_{MAX}: 12.2W.kg^{-1}; jump height: 0.29m, 20m sprint time: 3.78sec [16]. When comparing correlations between matched mechanical characteristics, soccer athletes displayed slightly lower associations than field hockey athletes (F_0: $r \leq 0.42$; v_0: $r \leq 0.27$; P_{MAX}: $r \leq 0.44$; performance outcome: $r \leq -0.59$), whereas sport science students displayed similar matched mechanical characteristics (F_0: $r \leq 0.57$;v_0: $r \leq 0.48$; P_{MAX}: $r \leq 0.78$; performance outcome: $r \leq -0.83$). Greater correlations and similarities between club-level field hockey athletes and sport science students, rather than higher level soccer athletes, is likely explained by the heterogeneity of the population.

Within this study, maximal external power demonstrated the strongest relationship between jumping and sprinting actions highlighting the importance of this mechanical quality to field hockey athletes. Relative to distance, it has been suggested greater intensities and running velocities are achieved in field hockey compared to other field sports such as soccer [3]. Samozino et al. [52] recently identified acceleration performance less than 30m largely depends on P_{MAX} and individual mechanical characteristics, further identifying the necessity to develop and express this mechanical quality to be an effective field hockey player. These findings have been supported in similar studies, but not all (r = 0.27) [53] involving amateur netball players, academy rugby players, high-level sprint athletes and professionl male and female football players, (r = 0.40–0.75) [14,18-20], further highlighting the need for power development expression in field and court sports. However, across these studies, most force variables (F_0) did not achieve significance ($r \leq 0.27$), thereby demonstrating a greater emphasis on movement velocity capabilities to express maximal external power. This was not the case in this study, as both F_0 and v_0 achieved significance however stronger associations are evident between movement velocity in both jump and sprint actions.

Non-significant relationships were evident between slope of the jump and sprint F-v profile (S_{FV}) suggesting independent characteristics of this mechanical variable (Table 2). Although differences in ability level are evident, low correlations between the jump and sprint S_{FV} have previously been reported in elite female soccer players [20] (r =-0.09) and high-level sprint athletes [18] (r =0.17). Previous studies have raised concerns regarding the reliability (ICC: ≤ 0.50, CV%: ≤ 29.3) of the S_{FV} using countermovement and squat jump actions from F-v profiles [54,55], along with the utility of the mechanical variable to inform performance, however other studies have recently questioned the methodological rigors to obtain reliable data [56].

Regarding our second hypothesis, we aimed to determine whether the same mechanical variable would explain performance variability in each force orientation. Multiple linear regression analysis identified F_0 and v_0 had a significant influence on jump height and sprint time explaining 74% and 94% of the variance in outcome respectively. When analyzing jump height and sprint time as the dependent variables, vertical F-v regression model coefficients showed v_0 had greater effects on performance outcome compared to F_0. Similarly, increases in horizontal v_0 had a greater effect on reducing sprint time over 30-meters compared to increases in F_0. This identifies the underpinning mechanical characteristics explaining the performance outcome is the same between jumping and sprinting actions, thereby confirming our hypothesis. Furthermore, it may also identify this population group exhibits a force-dominant F-v profile and the subjects require greater exposure to maximal movement velocity during training (i.e., sprint training), which would influence the approach to development and expression of maximal power.

From a physical preparation perspective, club-level field hockey athletes could target power development [57] to improve jump height, plus select exercises which target high movement velocities and optimal loads to improve sprint performance [33,58]. Previous studies with elite youth soccer players identified high-velocity training improved adaptations to the high-velocity/low-force end of the F-v continuum, which lead to improved power expression [59]. The present study highlighted relative P_{MAX} showed slightly stronger relationships to sprint time than was evident for jump height however the correlations between force and velocity to express P_{MAX} are different between actions (Figure 4). The stronger kinematic relationship between relative P_{MAX} and v_0 in sprinting compared to jumping is likely due to the necessity to achieve maximal power expression in early acceleration [58] plus the overall duration of the task places a greater emphasis on velocity qualities. Similar P_{MAX} correlations in other population groups including netball, soccer and ballet suggests this relationship may be typical amongst athletes irrespective of their ability level or sport (i.e., novice vs elite) [14,18-21].

Overall, this cross-sectional study has several strengths. Although suggestions the magnitude of transfer may be dependent on the task [40] therefore adhering to the force-vector theory and dynamic correspondence [34,38], this study identifies vertical F-v profiles can potentially infer performance in horizontal F-v profiles and vice versa. Moreover, if practitioners working with field hockey athletes should only choose one F-v assessment to determine mechanical characteristics, the authors of this study recommend horizontal F-v profiling. Despite similar expression of force relative to the local coordinate system of the athlete [34], the technical component of applying horizontally directed force at increasing running velocities during sprinting i.e., mechanical effectiveness [33], typically requires greater segmental coordination [60] than vertical force expression and therefore may provide greater mechanical insight for the practitioner. Finally, there are few studies exploring mechanical profiling in field hockey populations and therefore this adds original knowledge towards biomechanical and strength and conditioning practices within the sport.

There are also limitations in this study which should be acknowledged. Firstly, although significant relationships were evident between vertical and horizontalF-v profiles, a closer analysis of the loads selected in the vertical F-v profile and distance in the horizontal F-v profile may have improved the correlation between matched mechanical variables. For example, stronger relationships with relative P_{MAX} and the vertical F-v profile may exist due to the selected loads which may have optimized external mechanical power [57] for subjects, rather than exposure to loads spanning the F-v continuum [61]. Moreover, the slightly greater relationship with v_0 than P_{MAX} in the horizontal F-v profile is likely a result of the overall sprint distance and potentially individual subject F-v characteristics. In most team sports, including field hockey, acceleration and sprint distances are generally less than 15-meters where maximal force qualities in the horizontal direction are dominant, whereas velocity qualities are dominant when sprint distances are greater than 15-meters [3,52]. Therefore, the selected sprint testing distance placed a greater reliance on velocity capabilities to achieve a faster 30-meter time. Secondly, the cross-sectional approach, heterogenous population and competition level of participants (i.e., club-level, novice) used in this study may limit findings and transfer of understanding in higher ability athletes (i.e., elite level). Finally, stronger correlations between mechanical characteristics and performance outcomes (i.e., vertical characteristics and horizontal performance outcome, and vice versa) may have been observed due to greater variability in the mechanical dataset compared to previous studies [62]. Greater information could be provided to practitioners by analyzing longitudinal changes to the relationships between matched characteristics obtained from mechanical profiles across a competitive field hockey season and determine how this might assist strength & conditioning practice.

CONCLUSIONS

This is the first cross-sectional study to investigate the transfer of mechanical characteristics between vertical and horizontal force-velocity profiles and performance outcomes in club-level (i.e., novice) field hockey athletes. Matched variables from jump and sprint mechanical profiles revealed significant correlations between force, velocity, and power suggesting they explain similar mechanical characteristics irrespective of force orientation. Relative maximal power demonstrated the greatest correlation to the performance outcome in jumping and sprinting respectively, however the contribution of force and velocity differed between actions. In addition, multiple linear regression models indicated v_0 was a greater predictor of jump and sprint performance variability compared to F_0. This information may have implications on physical preparation strategies and exercise selection along with identifying which aspect of the force-velocity continuum to target. Trivial correlations for the vertical and horizontal S_{FV} suggest the linear F-v relationship is unrelated between actions. Overall, strength & conditioning coaches working with club-level field hockey athletes could potentially use mechanical profiles interchangeably to determine current mechanical strengths, weaknesses, and imbalances, yet due to technical differences when expressing force in the horizontal direction, greater mechanical insight may be provided by performing mechanical profiling in both force-vectors.

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