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Research article

Force-Velocity Profiling in Club-Based Field Hockey Players: Analyzing the Relationships between Mechanical Characteristics, Sex, and Positional Demands

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Abstract

The purpose of this study was to investigate differences between sex and positional demands in club-based field hockey players by analyzing vertical force-velocity characteristics. Thirty-three club-based field hockey athletes (16 males - age: 24.8 ± 7.3yrs, body mass: 76.8 ± 8.2kg, height: 1.79 ± 0.05m; 17 females - age: 22.3 ± 4.2yrs, body mass: 65.2 ± 7.6kg, height: 1.66 ± 0.05m) were classified into two key positional groups (attacker or defender) based on dominant field position during gameplay. Force-velocity (F-v) profiles were established by performing countermovement jumps (CMJ) using a three-point loading protocol ranging from body mass (i.e., zero external mass, 0%) to loads corresponding to 25% and 50% of their own body mass. Across all loads, between-trial reliability of F-v and CMJ variables was determined by intraclass correlation coefficients (ICCs) and coefficient of variation (CV) and deemed to be acceptable (ICC: 0.87 - 0.95, CV% 2.8 - 8.2). Analysis by sex identified male athletes had significantly greater differences in all F-v variables (12.81 - 40.58%, $p \leq 0.001$, ES = 1.10 - 3.19), a more enhanced F-v profile (i.e., greater theoretical maximal force, velocity, and power values), plus overall stronger correlations between relative maximal power (P_{MAX}) and jump height ($r = 0.67$, $p \leq 0.06$) when compared to female athletes ($-0.71 \leq r \geq 0.60$, $p = 0.08$). Male attackers demonstrated a more 'velocity-oriented' F-v profile compared to defenders due to significant mean differences in theoretical maximal velocity (v_0) (6.64%, $p \leq 0.05$, ES: 1.11), however differences in absolute and relative theoretical force (F_0) (15.43%, $p \leq 0.01$, ES = 1.39) led to female attackers displaying a more 'force-oriented' profile in comparison to defenders. The observed mechanical differences identify the underpinning characteristics of position specific expression of P_{MAX} should be reflected in training programmes. Therefore, our findings suggest F-v profiling is acceptable to differentiate between sex and positional demands in club-based field hockey players. Furthermore, it is recommended field hockey players explore a range of loads and exercises across the F-v continuum through on-field and gym-based field hockey strength and conditioning practices to account for sex and positional mechanical differences.

Key words: Force, velocity, power, neuromuscular, mechanical, field hockey

Introduction

Field hockey is a high-intensity, intermittent-based team sport with high mechanical demands requiring players to accelerate, decelerate, change speed and direction quickly, and in addition requires advanced skill to be an effective player (Sharma and Kailashiya, 2017). Recent literature on field hockey has characterized movement patterns, activity profiles and repeated-sprint ability (Spencer et al., 2014; Spencer et al., 2004) using time-motion analysis (i.e., global positioning systems [GPS] (Gabbett, 2010; Macutkiewicz and Sunderland, 2011; Vescovi, 2014) which quantified different game-based demands for specific positional groups including speed and distance of sprint efforts. Studies on age groups ranging from youth to international level field hockey also identified a significant demand for high-speed running during the game, with midfielders and attackers accumulating a greater number of high intensity actions compared to defenders (Jennings et al., 2012; Lythe and Kilding, 2011; Macutkiewicz and Sunderland, 2011; McGuinness et al., 2019; van der Merwe and Haggie, 2019). Despite extensive analysis of movement patterns within the sport of field hockey, mechanical characteristics contributing to on-field performance including force, velocity and power are yet to be fully explored.

Comparisons between high-intensity actions such as sprinting, and positional groups during field hockey games have previously highlighted significant differences between the number of sprints performed, velocities achieved during sprint efforts and the position of the player on the field (Gabbett, 2010; Macutkiewicz and Sunderland, 2011; Spencer et al., 2004; Vescovi, 2014), suggesting the biomechanical demands and therefore F-v characteristics required at each position are different. For example, in elite women's hockey, midfielders spend a greater portion of game time at velocities greater than 7 $m.s^{-1}$, when compared to attackers and defenders, while midfielders and attackers spend a greater portion of game time above 5 $m.s^{-1}$, when compared with defenders (Gabbett, 2010). This comparison between position groups also identified attackers (also known as strikers) as likely to have a greater maximal velocity during game-play compared to midfielders and defenders, demonstrating their exposure to a greater mechanical load (Macutkiewicz and Sunderland, 2011). Similarities have been observed in elite men's field hockey where differences between high intensity actions and positional groups identified inside-forwards (n = 39 ± 1) and strikers (n = 42 ± 15) performed a greater number of sprint actions when compared with full-backs (n = 18 ± 1) and half-backs (n = 22 ± 7) (Spencer et al., 2004). Therefore, quantifying the on-field movement characteristics via time-motion analysis, along with analyzing the underpinning mechanical determinants and F-v relationship of the lower limbs contributing to performance may provide greater insight to further enhance field hockey strength and conditioning practice.

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In sprint and team sport athletes, previous studies have demonstrated a significant correlation between the F-v characteristics of jumping and sprinting actions (Loturco et al., 2018). The association between both actions has identified relative peak force, peak power and jump height in a countermovement jump (CMJ) action as strong predictors of maximal velocity at 10-metres and improved sprint times from 5 - 60-metres (Markstrom and Olsson, 2013; Morris et al., 2022), thereby highlighting similar neuromuscular qualities between actions. Due to the strong relationships between jump and sprint performance (Cronin and Hansen, 2005; Markstrom and Olsson, 2013), a CMJ is often an effective assessment of mechanical output to infer F-v characteristics across both actions. Furthermore, the simplicity of performing the jumping movement without the risk of injury associated with maximal velocity sprint testing may be more favourable from a coaching perspective (Morris et al., 2022). Despite the ease of testing, an isolated CMJ assessment is limited as it evaluates lower-limb function under a single mechanical condition; an athlete's body mass, and therefore the observed outcomes do not differentiate between different muscle capacities (i.e., force production at low and high velocities) (Jaric, 2016). Therefore, to determine overall mechanical characteristics a F-v profile may be an alternative approach.

Force-velocity profiling has previously shown strong utility in team sports (Escobar-Álvarez et al., 2018; 2020; Jiménez-Reyes et al., 2016; 2018b; 2019; Marcote-Pequeño et al., 2018) to characterize the maximal mechanical capabilities of the lower limbs neuromuscular system (Samozino, 2018). When performing a vertically oriented F-v profile, the athlete jumps (CMJ or squat jump) against a range of external loads (between 2-9 loads) (Garcia-Ramos et al., 2021; Morin and Samozino, 2016) from their own body mass only (i.e., zero external load) to potentially jumping with external load up to 75-100% of their body mass (Garcia-Ramos et al., 2016). Typically, the F-v profile provides comprehensive information about overall neuromuscular function including: the slope of the F-v profile (S_{FV}), theoretical maximal force at null velocity (F_0), theoretical maximal movement velocity up to which force can be produced (v_0) and theoretical external maximal power (P_{MAX}), the product of the two former variables (Jaric, 2016). Potentially, athletes with different F-v profiles could produce similar levels of external P_{MAX}, yet with a different combination of vertical force and velocity, thereby offering insight to the practitioner about the strengths and weaknesses of their neuromuscular system (i.e., force-oriented or velocity-oriented) (Jiménez-Reyes et al., 2016). F-v profiling in a range of tasks has shown to not only quantify current mechanical capabilities, but to distinguish between ability level (e.g. elite, non-elite)(Jiménez-Reyes et al., 2018a) and sport (Giroux et al., 2016), while potentially being used to guide training interventions and programming decisions (Jiménez-Reyes et al., 2019). Despite this, concerns have been raised about the reliability of using mechanical profiling to determine F-v variables through countermovement and squat jump actions, as well as the utility of these variables to inform performance. (Lindberg et al., 2021; Valenzuela et al., 2020). However, recent research has also challenged these concerns by demonstrating that improved methodological practices can produce reliable data.(Samozino et al., 2022). Currently, there is limited information about the biomechanical demands of field hockey, suggesting a greater understanding of F-v characteristics between sex and positional demands within the sport may provide strength and conditioning practitioners with useful information to optimize and individualize training programmes to enhance on-field performance.

Therefore, the aim of the study was to evaluate vertically oriented force-velocity characteristics in male and female field hockey athletes and use the information to inform training-related interventions. Specifically, we aimed to determine and compare mechanical F-v relationships between sex and positional groups within a field hockey context. Due to achieving higher velocities during game-play as identified in time-motion analysis (Jennings et al., 2012), we hypothesized athletes who were classified as primary attackers on the field would (1) display a more velocity-oriented F-v profile when compared with defenders, thereby demonstrating significantly higher values in relative maximal power (Samozino et al., 2021) and (2), we hypothesized differences would exist in the F-v profile between males and females due to strength related factors (Garhammer, 1991; Kraemer and Ratamess, 2004; Nuell et al., 2019; Thomas et al., 2007), and males would display an overall more enhanced F-v profile. The results of this study would allow for a more effective training design for field hockey athletes based on mechanical characteristics.

Methods

We used a cross-sectional experimental design to investigate the relationship(s) between the vertical F-v profile using a CMJ, sex (male, female) and playing position (attackers and defenders). In consultation with the head coaches of the respective field hockey teams, subjects were classified as either an attacker or a defender based on where their coach most frequently positioned them on the field. Attacking positions included: attacking midfielder, left and right wing, inside left and right and striker. Defensive positions included: defensive midfield, outside and central defenders, sweeper and goalkeeper. It was reported by the coaching staff that some athletes played multiple attacking or defensive positions. All athletes were assessed for anthropometric measures (body mass, standing stature) along with a three-point F-v profile using incremental loads. The testing session for all athletes was conducted during the field hockey preseason period, approximately 8-weeks before the season began, with the intention the results would provide greater insight into training direction for specific positional groups across the preseason period. All CMJ measurements were recorded indoors with the same external environmental conditions and supervised by a certified strength and conditioning professional.

Subjects

Thirty-three club-level field hockey athletes (male n=16, 8 attackers/8 defenders), age: 24.8 ± 7.3 years, body mass: 76.8 ± 8.2 kg, and height: 1.79 ± 0.05m, (female n = 17,

Table 1. **Descriptive statistics of anthropometric variables between sex and positional group.**

Variable	Males					Females				
	Attackers	Defenders	Mean difference (±95%CL)	Mean % difference	ES (90% CI)	Attackers	Defenders	Mean difference (±95%CL)	Mean % difference	ES (90% CI)
Age (y)	24.50 ±8.94	25.16 ±4.91	-0.66 (-8.10, 6.77)	2.44	-0.08 (-1.19, 1.02)	23.10 ±4.56	21.50 ±4.44	1.61 (-3.05, 6.27)	6.96	0.35 (-0.68, 1.40)
Body mass (kg)	75.64± 9.52	80.50 ±3.53	-5.85 (-13.09, 1.39)	7.83	-0.73 (-1.88, 0.40)	66.86 ±8.72	61.40 ±4.56	5.46 (-1.4, 12.33)	8.19	0.71 (-0.39, 1.83)
Height (m)	1.77 ±0.04	1.81 ±0.08	-0.04 (-11.8, 4.54)	2.25	-0.66 (-1.80, 0.46)	1.64 ±0.05	1.65 ±0.05	0.01 (-6.1, 3.9)	0.06	-0.66 (-1.80, 0.46)

CL: confidence limits, ES: effect size, CI: confidence interval

9 attackers, 8 defenders), 22.3 ± 4.2 years, body mass 65.2 ± 7.6 kg, and height 1.66 ± 0.05 m, participated in the study (Table 1). Subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study. The adult guardians or parents provided signed written consent for subjects under 18 years of age. Inclusion criteria included: subjects involved in state league level of competitive sport; a background in resistance training of greater than six months; and aged 15-35 years. Exclusion criteria maintained that subjects needed to be six-months free of musculoskeletal injuries which may prevent them from performing maximal effort CMJ actions against external loads. In their pre-testing questionnaire, subjects acknowledged their experience with exercises such as the vertical jump. Subjects were asked to refrain from physical training within the 24-hours prior to testing. 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).

Procedures

The vertical F-v profile assessment was performed on the same day for all subjects. The conditions observed on the day of testing included the following environmental variables: temperature min 21.5°C, max 33.0°C, SE winds 13km/h, 1017.5hPA.

Vertical force-velocity profile assessment

Prior to jump testing, subjects completed a standardized warm-up consisting of three minutes of step-ups (cadence of 85 on metronome), dynamic movements, and preparatory vertical jumps including a series of maximal unloaded and sub-maximal (10 - 15kg) loaded CMJ trials (Hicks et al., 2021). During all trials, internal cues such as “squat to a seated position then extend your hips, knees and ankles as fast as you can” (McMahon et al., 2018b), plus external cues such as “jump to the roof” were provided to subjects to ensure maximal intent was provided across the three loading conditions (Halperin et al., 2015).

All assessments began with subjects standing with each foot on a separate portable force plate system (35cm by 35cm, PASPORT force plate, PS-2141, PASCO Scientific, California, USA), which directly measured left and right foot ground reaction forces (GRF). This type of portable force plate has previously been validated and deemed reliable against in-ground laboratory grade force plates (Lake et al., 2017). Prior to the initiation of the jump, subjects were instructed to stand still at full stature for at least 1-second with their left and right foot on the center of each force plate, to ensure the weighing phase could be calculated accurately (McMahon et al., 2018b). If there was movement prior to the initiation of the jump, the trial was repeated. Preceding the next trial, the force plate was zeroed. Vertical GRF was continuously sampled at 1000 Hz for each force plate, with vertical force-time data being stored within a local computer. The data was subsequently exported to a csv file for post-processing analysis.

Countermovement jump trials were performed either with body mass only (arms akimbo), a purpose-built polyvinyl chloride (PVC) hexagon made to the same inner dimensions as the free weight hexbar, which could hold light external load if required, or a 15kg free-weight hexbar with load added determined by percentage of body mass. Subjects used the high handles of the free-weight bar and were standing upright, within the hexagonal shape, with the bar sitting off the ground prior to descending into the CMJ. Each subject’s arms remained extended throughout the duration of the jump. Countermovement depth was self-selected and was not constrained by a box or band to encourage individual jump strategy (McMahon et al., 2017).

We used a three-point loading protocol for the F-v profile as this has been shown to provide reliable and valid data when compared to the more commonly used multiple point (load) approach (Šarabon et al., 2020). The multiple-point method although used extensively in the field, may be time-consuming on the practitioner, plus may also lead to athlete fatigue due to the necessity to perform multiple jumps at each incremental loading condition. Therefore, the three-point (body mass plus two external loads) approach was selected to obtain mechanical capabilities across the F-v spectrum. Each participant performed the trials using the same incremental loads and order; body mass (BM, 0%) (Load 1), then 25% (Load 2) and 50% (Load 3) externally added mass. Three trials were performed at each loading condition, assuming a successful jump. Upon landing for all loading conditions, subjects were asked to touch down with the same leg position as when they left the ground (i.e., plantar flexed ankle joint). Between each loading condition, there was a 3-minute passive recovery period to limit fatigue prior to the next series of jump trials.

To determine the F-v profile, mean values of force and velocity were determined using force-time data during the propulsive phase (concentric portion of jump) of the

CMJ. Key phases of the CMJ were agreed upon using the force-time characteristics previously outlined (McMahon et al., 2018b). The propulsive 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 (McMahon et al., 2018b). Mean vertical GRF was determined by averaging force from the dual force plate system across the time points established for the propulsive phase of the jump. The instantaneous vertical velocity across the propulsive phase of each jump type was determined via integration of the center of mass (COM) vertical acceleration signal over time via force plate data and then averaged across the propulsion phase. Mean external power across the propulsion phase was then calculated as the product of mean GRF and estimated mean COM velocity according to the sample rate from the force plates. Vertical GRF was used to calculate vertical instantaneous acceleration of the COM, therefore determining changes to eccentric (braking phase) and concentric (propulsive phase) COM displacement during the countermovement. The braking phase (eccentric portion of jump) commenced from the instant of peak negative COM velocity through to when COM velocity increased to zero. Flight time was determined using the thresholds previously outlined and is characterized by the instant of take-off and landing on the force plates. Jump height (JH) was determined using the trapezoid rule in reference to flight time using the gold standard equation, JH = $v^2 2g$ (v = vertical velocity, g = gravitational constant)(Moir, 2008). Concentric and eccentric contraction times were established using the time-points outlined in the force-time characteristics. Take-off velocity was determined as the maximal velocity at the conclusion of the propulsion phase (McMahon et al., 2018a).

Force-velocity relationship during countermovement jumps

Force-velocity parameters were established using direct mean ground reaction force from the force plates and then input into a customised Microsoft Excel spreadsheet as outlined by Garcia-Ramos et al. (Garcia Ramos and Jaric, 2017). Descriptions of F-v and CMJ variables are shown in Table 2. The trial at each load which recorded the highest take-off velocity (maximum vertical velocity) was used for statistical analyses as this likely represents the current maximal capabilities of the neuromuscular system during the movement (Reiser et al., 2006). 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 as: $P_{MAX} = F_0.v_0/4$. 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: $S_{FV} = F_0/v_0$.

Statistical analyses

Statistical analyses were determined from input into custom built Microsoft Excel spreadsheets (Hopkins, 2015) 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. The sample size used in this study was based on priori estimates used in previous research (total sample: n = ≤19, group comparisons: n = ≤9) using mechanical profiling suggesting the number of subjects is acceptable to detect true changes (Bellinger et al., 2021; Nuell et al., 2019; Stavridis et al., 2019).

All descriptive data are presented as mean ± standard deviation (SD) and were assessed for normality using the Shapiro-Wilks test. Mean force, velocity and power and associated F-v variables, plus vertical jump kinematics for all CMJ loading conditions, were calculated and derived using force-time characteristics previously detailed in recent literature (McMahon et al., 2018b).

Table 2. Definition and practical description of vertical force-velocity and countermovement jump variables.

Variable	Abbreviation	Practical Interpretation
Theoretical maximal vertical force (intercept) production extrapolated from the linear loaded countermovement jump F-v relationship	Absolute F_0 (N) Relative F_0 ($N.kg^{-1}$)	Maximal concentric force output in the vertical direction per unit of body mass. Describes the athlete's force capability to project the centre of mass in the vertical direction.
Theoretical maximal movement velocity (intercept) extrapolated from the linear loaded countermovement jump F-v relationship	v_0 ($m.s^{-1}$)	Maximal movement velocity in the vertical direction during the countermovement jump. Describes the athlete's ability to produce force at high velocities in the vertical direction.
Maximal mechanical external power output in the vertical direction ($P_{max} = F_0 \times v_0/4$)	Absolute P_{MAX} (W) Relative P_{MAX} ($W.kg^{-1}$)	Maximal external power-output capability during the concentric action of the countermovement jump per unit of body mass.
Slope of the force-velocity relationship	Absolute S_{FV} ($N.s.m^{-1}$) Relative S_{FV} ($N.s.m^{-1}.kg^{-1}$)	Index of an athlete's individual balance between force and velocity capabilities. The more negative the value, and steeper the F-v slope, the more force-dominant the athlete is.
Jump height	JH (m)	The maximal centre of mass displacement achieved during the flight phase of the countermovement jump.
Flight time	FT (sec)	Ariel time of the athlete between 'take-off' until 'landing' in the countermovement jump.
Take-off velocity	TOV ($m.s^{-1}$)	The maximal movement velocity at the conclusion of the propulsion phase

Intraclass correlation coefficient (ICC) with 95% confidence limits, using a 2-way random-effects model (absolute agreement) and coefficient of variation (CV) were used to assess relative and absolute reliability of CMJ variables. Reliability measures are important during multi-joint actions to ensure the linearity of the F-v relationship (Garcia Ramos and Jaric, 2017). Thresholds for evaluation of intraclass correlation coefficients were quantified using the following scale: 0.20 - 0.49 *low*, 0.50 - 0.74 *moderate*, 0.75 - 0.89 *high*, 0.90 - 0.98 *very high* and ≥ 0.99 *extremely high* (Hopkins et al., 2009). Biomechanical literature have previously reported variables with a CV within the range of 10% as reliable (Cormack et al., 2008). Therefore, acceptable reliability was determined with a coefficient of variation (CV) ≤ 10% (Cortina, 1993) and ICC > 0.70 (Atkinson and Nevill, 1998; Cormack et al., 2008; Vincent, 1999).

To assess the effect of positional demands and sex on vertical force-velocity profile variables, a 2 (position) x 2 (sex) ANOVA for each variable was used. Furthermore, a one-way ANOVA was used for each sex to determine significant differences based on positional demands. To analyse the associations between F-v and CMJ variables, Pearson's product-moment correlation coefficient (Pearson's *r*) was utilized. Thresholds for evaluation of Pearson's correlation coefficients (*r*) were quantified using the following scale: weak (≤0.39), moderate (≥0.40 - 0.69), or strong (≥0.70) (Cohen, 1988). Effect sizes (Cohen's d) were determined from both sexes and positional groups with 95% confidence limits. Magnitudes of effect size changes were interpreted using the following values: trivial (< 0.20), small (0.20 ≤ 0.60), moderate (0.60 ≤ 1.20), large (1.20 ≤ 2.00) and extremely large (> 2.00)(Cohen, 1988). An alpha value of $p \leq 0.05$ was used to indicate statistical significance.

Results

Table 1 highlights descriptive statistics for anthropometric variables between sexes and playing positions with moderate, non-significant effects reported for body mass (kg) between positional groups in both sexes (-0.73 ≤ ES ≥ 0.71). Table 3 reports the between-trial reliability for kinetic and kinematic variables established from the force-time data. Relative and absolute reliability for males across all key variables were classified as high, (ICC: 0.95 - 0.97, CV% 2.7 - 6.9), while females demonstrated slightly lower yet acceptable reliability values, (ICC: 0.87 - 0.95, CV% 2.8 - 8.2). The linearity (R^2) of F-v profiles for males and females was 0.99 (Figure 1), suggesting strong reliability across the selected loads and no significant difference between sexes. Figure 2 identifies Pearson's correlation coefficients between all mechanical variables and vertical jump performance (i.e., jump height). Male and female attackers reported a slightly stronger, more dominant relationship between relative P_{MAX} and v_0 ($r \geq 0.91$, $p \leq 0.01$) compared to relative F_0, whereas male defenders only displayed a strong association with relative P_{MAX} and relative F_0 ($r \geq 0.94$, $p \leq 0.01$). Female defenders presented balanced correlations between relative F_0, v_0 and relative P_{MAX}. More details on correlation and significant relationships between F-v variables can be found in supplemental files (S1). Figure 3 identifies the linear regression model between jump height and relative P_{MAX} highlighting weak to moderate R-squared values between sex and positional group (males: $R^2 \geq 0.45$; females: $R^2 \geq 0.35$). Female defenders only demonstrated a negative linear relationship between jump height and relative P_{MAX}.

Table 3. Traditional measures of relative and absolute reliability between sexes for force-velocity and countermovement jump variables.

Variables	Male		Female	
	ICC (± 95%CL)	CV (± 95%CL)	ICC (± 95%CL)	CV (± 95%CL)
Mean force (N)	0.97 (0.94, 0.98)	2.7 (2.2, 3.4)	0.92 (0.86, 0.95)	4.5 (3.7, 5.6)
Mean velocity (m.s^{-1})	0.97 (0.94, 0.98)	3.4 (2.8, 4.3)	0.92 (0.86, 0.95)	4.9 (4.1, 6.1)
Mean power (W)	0.95 (0.92, 0.97)	4.2 (3.5, 5.4)	0.87 (0.78, 0.92)	5.7 (4.8, 7.2)
Jump height (m)	0.95 (0.91, 0.97)	6.9 (5.7, 8.8)	0.90 (0.83, 0.94)	8.2 (6.8, 10.3)
Flight time (sec)	0.97 (0.94, 0.98)	2.8 (2.3, 3.6)	0.95 (0.92, 0.97)	2.8 (2.3, 3.5)
Take-off velocity (m.s^{-1})	0.96 (0.92, 0.98)	3.2 (2.6, 4.0)	0.90 (0.83, 0.94)	4.0 (3.4, 5.1)

ICC = intraclass correlation coefficient, CL = confidence limits, CV = coefficient of variation

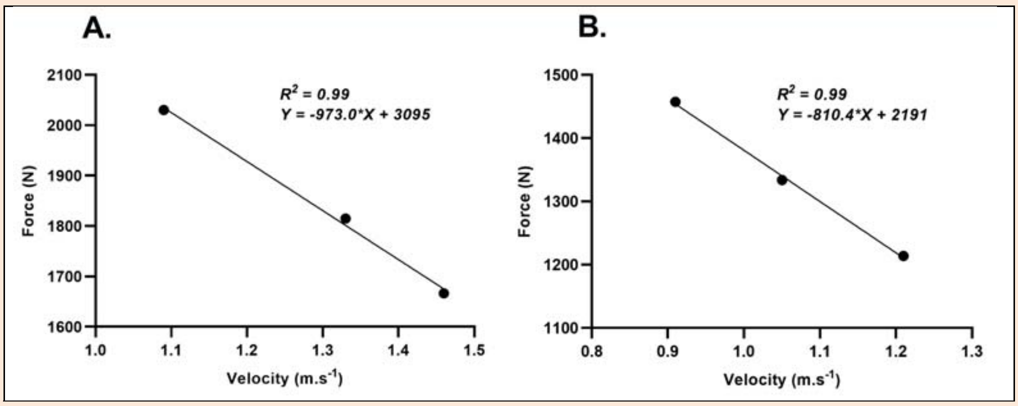

Figure 1. Linearity of the force-velocity profile across countermovement jump loading parameters. A: males; B: females.

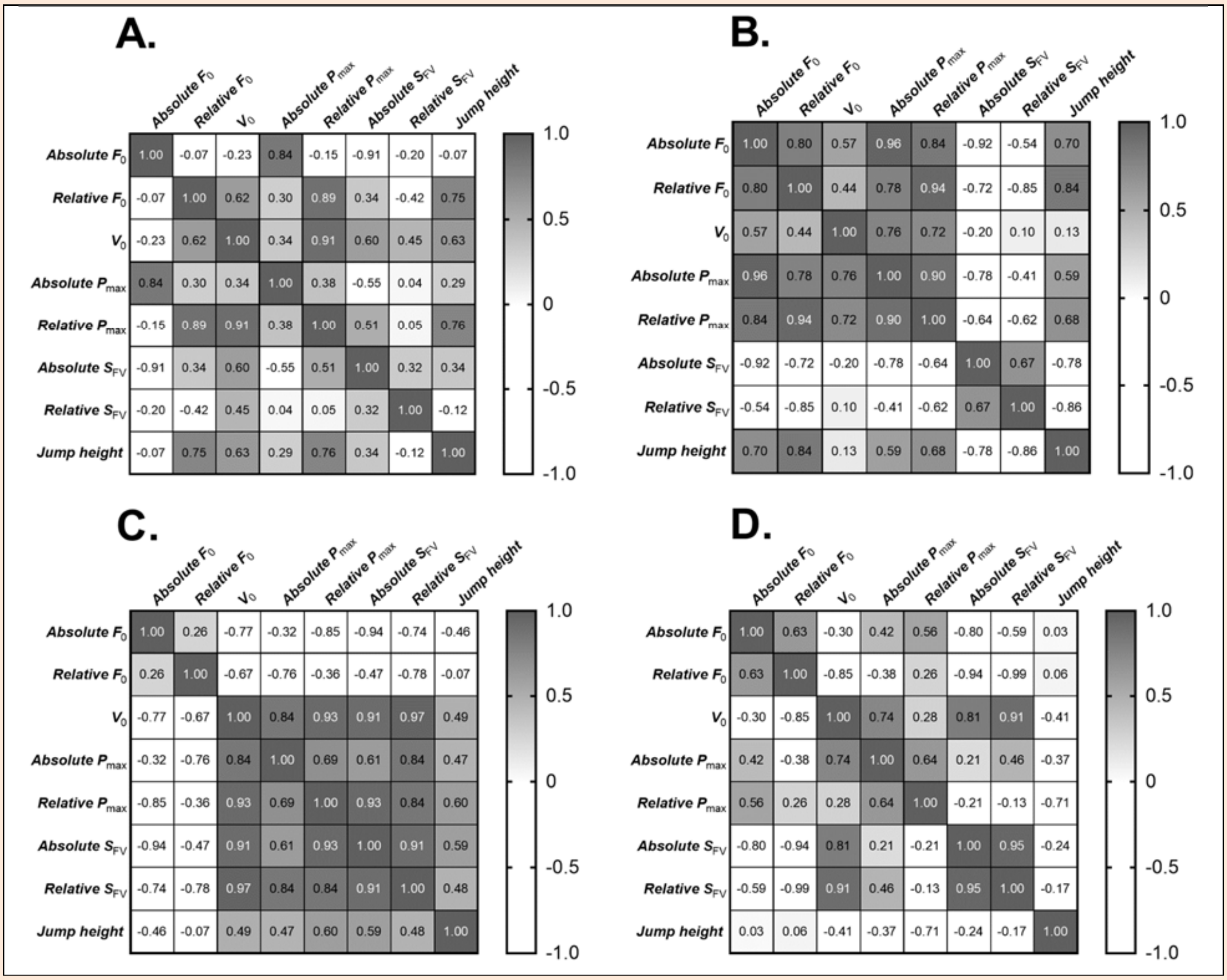

Figure 2. Correlation matrices of force-velocity and countermovement jump variables between sex and positional group. A: male attacker; B: male defender; C: female attacker; D: female defender.

The analysis of variance (Supplemental file: S2) across all F-v variables identified no significant effects based on position except for relative F_0 ($F = 4.41$, $p = 0.04$, ES = -0.80). Significant effects between sex were reported for most F-v variables ($F \geq 4.53$, $p \leq 0.04$, ES$\geq$ 0.76), excluding absolute and relative S_{FV}. A significant position-sex interaction effect was also evident for F_0 and mean force produced across CMJ trials ($F \geq 4.34$, $p \leq 0.04$, ES$\geq$ 0.88). Furthermore, post hoc comparison revealed that greater absolute and relative force differences were observed between female positional groups when compared to males. Tables 4 and 5 highlight descriptive statistics for positional group and sex. Regarding male athletes, significant differences were evident for v_0 with attackers demonstrating higher values than defenders (6.64%, $p \leq 0.05$, ES = 1.11). Female attackers showed significantly higher values for both absolute and relative F_0 (14.59 - 15.43%, $p \leq 0.01$, ES $\geq$ 1.35), when compared to defenders. Figure 4 highlights the differences in sex and positional groups in F-v and power-velocity (P-v) characteristics. Male attackers demonstrated a more 'velocity-oriented' profile compared to defenders due to significant differences in v_0 ($p \leq 0.05$, ES: 1.11) however differences in absolute and relative F_0 ($p \leq 0.01$, ES = 1.39) led to female attackers displaying a 'force-oriented' profile in comparison to defenders. Non-significant moderate effects was reported for S_{FV} (Es = 0.73) and P_{MAX} (ES = 0.93) for male and female positional groups respectively (Figure 5). Significant mean differences were also evident between males and females for mean force, velocity, and power variables, along with CMJ variables including jump height, flight time and take-off velocity (12.81-40.58%, ES $\geq$ 1.10, $p \leq 0.001$).

Discussion

The purpose of this study was to identify the relationship(s) between sex, positional demands and vertical F-v profiles in field hockey players to improve the individualization of training interventions by physical preparation coaches. To the authors knowledge, this is the first study to report on the sex-specific associations of the vertical F-v profile with positional demands in field hockey. The main findings of this study indicate that overall, (1) F-v characteristics and positional demands appear to be sex-specific suggesting different strength & conditioning strategies are likely required to improve mechanical output, (2) the relationship between sex and force production during CMJ actions is positional dependent, and (3) male players display a more enhanced F-v profile likely due to musculotendinous and structural differences between sexes.

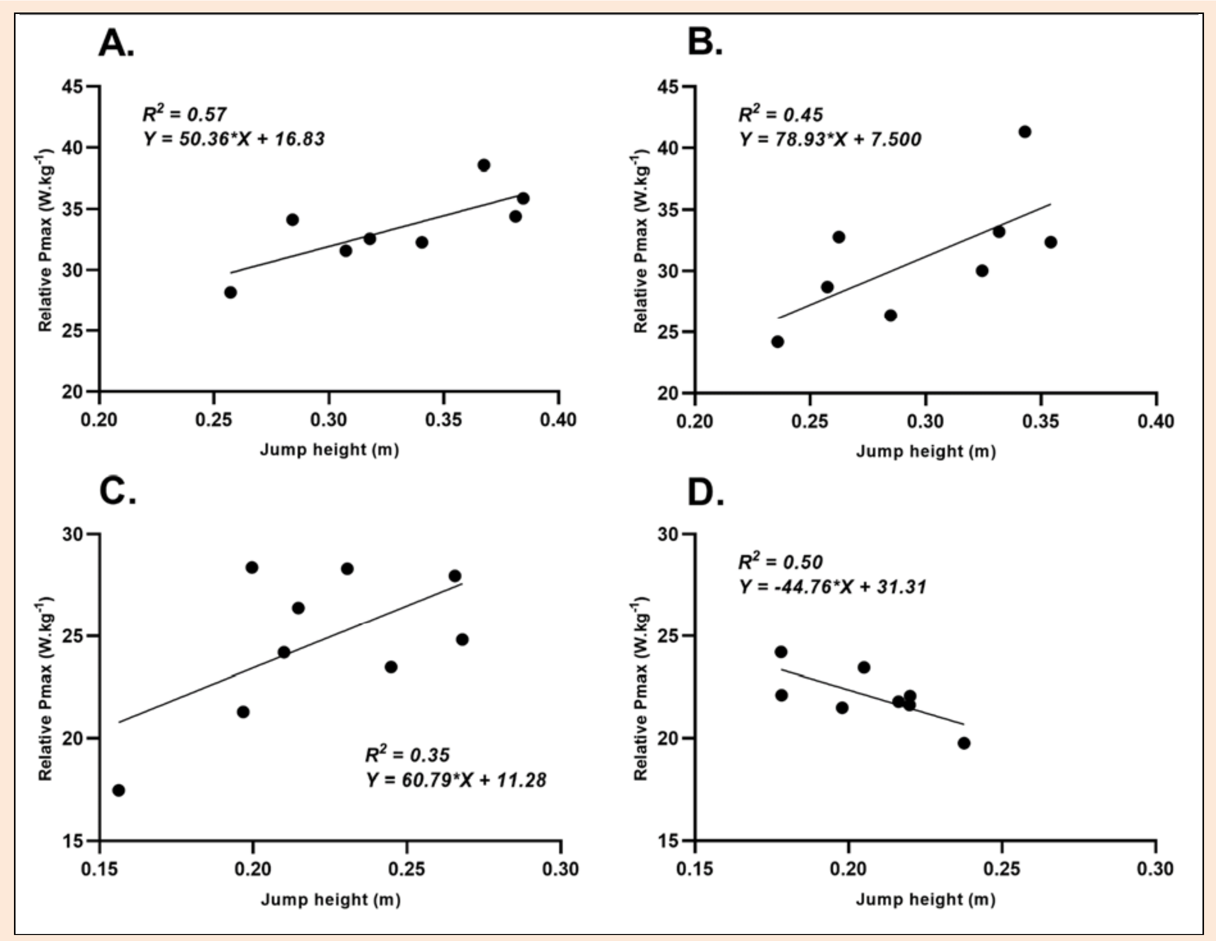

Figure 3. Linear regression model showing the relationship between jump height (metres) and relative maximal power (W·kg^{-1}) between sex and positional group. A: male - attackers; B: male - defenders; C: female – attackers; D: female - defenders.

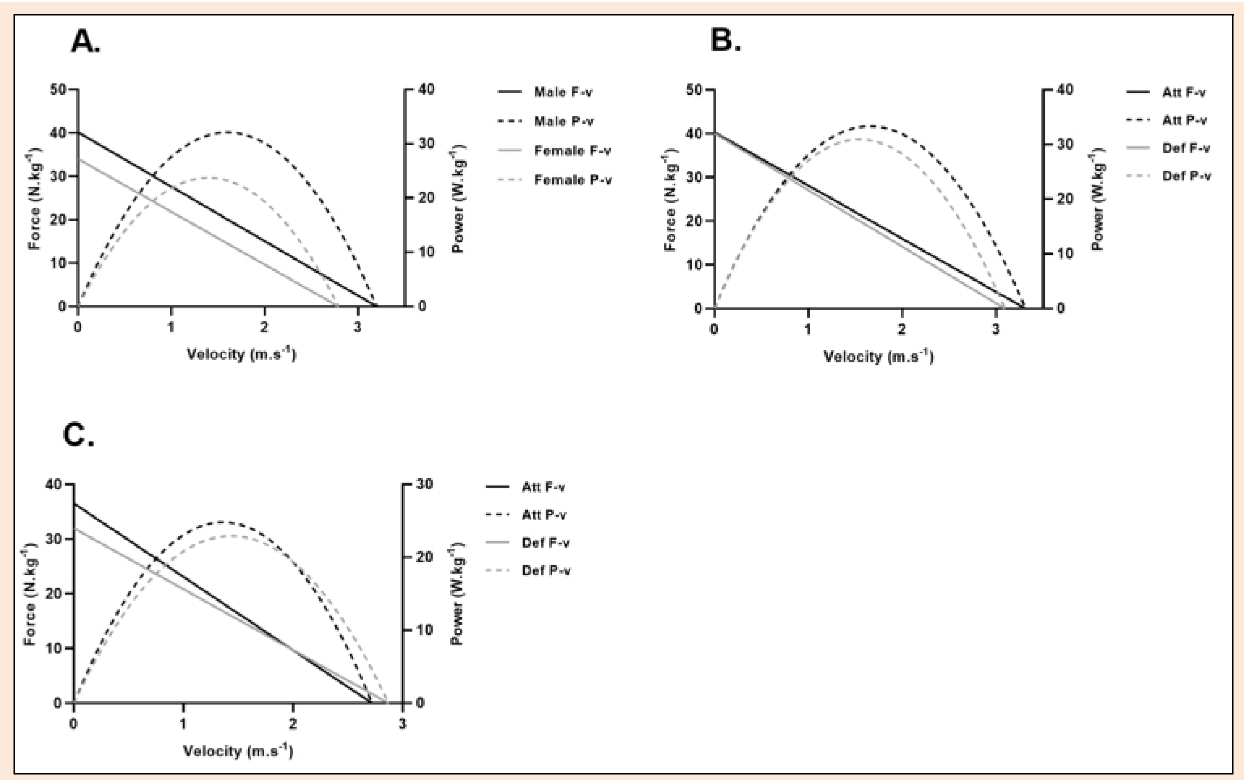

Figure 4. Mean force-velocity profiles from the countermovement jump loading protocol. A: between sex; B: males; C: females. F-v = force-velocity, P-v = power-velocity. Att = attacker, Def = defender.

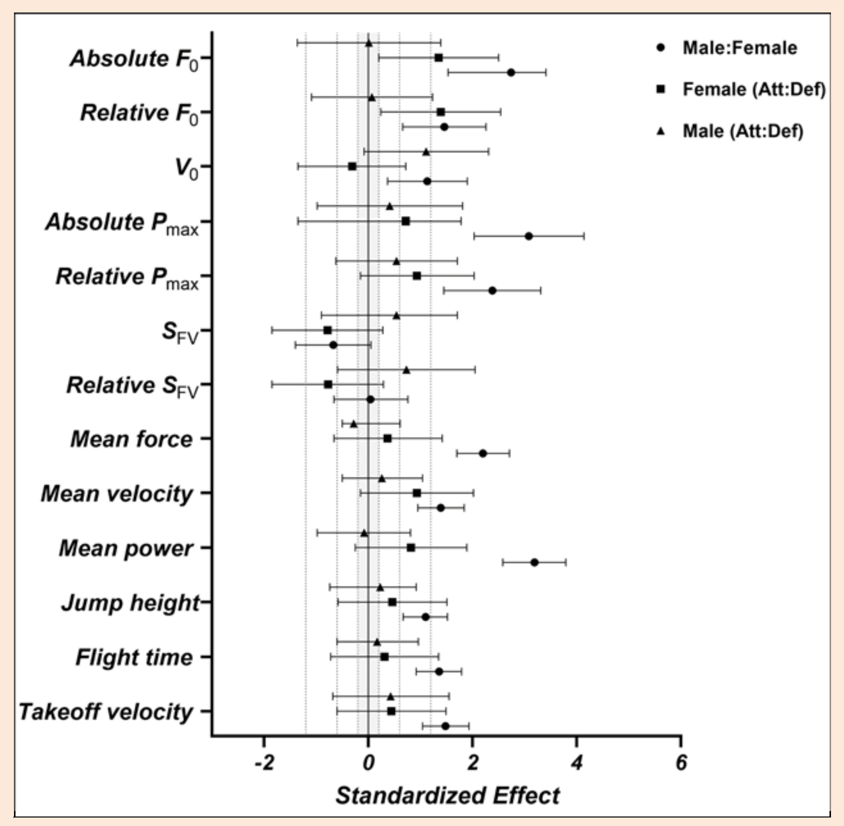

Figure 5. Standardized effect sizes (90% confidence intervals) in force-velocity and countermovement jump characteristics between sex and positional group.

The acceptable relative (ICC) and absolute (CV) reliability measures (Table 3) of this investigation suggests within this population of field hockey players, a three-point loading protocol provides reliable data (Figure 1) to establish a linear F-v relationship in a loaded CMJ action. Previous research using a two-point method, an unloaded jump and a heavy load, of approximately 75-100% of a participants' body mass, has highlighted this approach to assessing force, velocity and power capabilities of the lower limbs to be reliable and valid (ICC≥ 0.72, CV≤ 12.1%). However, it is recommended to select distal loads due to reliability and validity of measures decreasing with the proximity of applied loads (Garcia-Ramos et al., 2021). Similar reliability results using a CMJ have been observed when establishing a 2-point load-velocity relationship ICC≥ 0.63, CV≤ 7.30%) (Pérez-Castilla et al., 2021), with researchers highlighting the quick and safe nature of evaluating neuromuscular characteristics with this approach compared to a multiple load assessment.

In line with our first hypothesis, due to the greater demands for high-speed running and sprint efforts (Gabbett, 2010; Jennings et al., 2012) and despite the orientation for force being directed vertically during testing, we postulated attackers would display greater velocity characteristics than defenders. This hypothesis was confirmed in male subjects only, with both positional groups displaying similar levels of absolute and relative F_0, however attackers displayed higher a v_0, thereby creating a more 'velocity-oriented' profile (Figure 4). The differences observed in male subjects highlights the positional F-v requirements of attackers to produce and express force at high velocities. Research from elite level men's field hockey (Jennings et al., 2012) supports these findings, where attackers performed more high-speed running meters compared to defenders (-26.6 ± 8.2%, ES = -2.43), while during under-18 competition, attackers covered approximately 29% more distance (≥ 380m) during gameplay at ≥ 24.7 km/hr compared to defenders.

When comparing female positional groups, our hypothesis did not agree with the findings. Female attackers presented higher levels of absolute and relative F_0, therefore displaying a more 'force-oriented' profile and defenders a more 'velocity oriented' profile. Between female positional groups, the differentiating factor was therefore the ability produce and express force at low velocities. In elite women's hockey, significant differences have not been reported between positional groups in high-velocity and high-acceleration efforts up to distances of 20-meters (Gabbett, 2010), suggesting our results may not be unusual and may infer game dynamics within women's field hockey differs to that of their male counterparts. Previous research focused on women's field hockey identified attackers performed 21 high velocity actions and 16 acceleration actions from 6-20m, whereas defenders performed 19 and 13 high velocity and accelerations actions over the same distance respectively, suggesting the mechanical demands are similar between positional groups (Gabbett, 2010). However, midfielders were also included as a sub-category in this study which may have distorted the utility of comparing results to those found within this study. Although the movement characteristics of positional demands within male and female field hockey research appear to be similar, we must also be careful inferring data between competitions and ability levels.

Table 4. Descriptive statistics and mean differences between positional groups across all loads in force-velocity and countermovement jump variables.

Variable	Males					Females				
	Attackers	Defenders	Mean difference (±95%CL)	Mean % difference	ES (90% CI)	Attackers	Defenders	Mean difference (±95%CL)	Mean % difference	ES (90% CI)
Absolute F_0 (N)	3085.18 ±309.64	3079.48 ±484.44	5.70 (-430.28, 441.68)	0.18	0.01 (-1.36, 1.39)	2368.09 ±297.44	2002.62 ±234.19	365.47 (89.83, 641, 09)	15.43**	1.35 (0.20, 2.50)
Relative F_0 ($N \cdot kg^{-1}$)	40.29 ±2.02	40.03 ±5.03	0.26 (-3.84, 4.37)	0.64	0.07 (-1.09, 1.23)	36.51 ±2.78	31.18 ±4.73	5.33 (1.12, 9.53)	14.59**	1.39 (0.24, 2.54)
Theoretical maximal v_0 ($m \cdot s^{-1}$)	3.31 ±0.17	3.09 ±0.20	0.22 (0.009, 0.42)	6.64*	1.11 (-0.08, 2.31)	2.72 ±0.50	2.87 ±0.40	0.15 (-0.62, 0.32)	5.51	-0.31 (-1.35 0.72)
Absolute P_{MAX} (W)	2555.07 ±257.83	2398.95 ±482.90	156.12 (-258.99, 571.23)	6.11	0.41 (-0.98, 1.81)	1589.43 ±198.62	1433.43 ±235.06	156.00 (-72.15, 384.16)	9.81	0.72 (-0.34, 1.78)
Relative P_{MAX} ($W \cdot kg^{-1}$)	33.45 ±3.08	31.12 ±5.21	2.33 (-2.26, 6.92)	6.96	0.54 (-0.62, 1.71)	24.68 ±3.63	22.06 ±1.33	2.62 (-0.24, 5.51)	10.61	0.93 (-0.15, 2.03)
Absolute S_{FV} ($N \cdot s^{-1} \cdot m^{-1}$)	-933.69 ±120.35	-991.97 ±128.55	58.28 (-75.25, 191.82)	6.24	0.46 (-0.90, 1.84)	-915.93 ±317.01	-712.88 ±164.96	203.05 (-465.29, 59.20)	22.16	-0.78 (-1.86, 0.28)
Relative S_{FV} ($N \cdot s^{-1} \cdot m^{-1} \cdot kg^{-1}$)	-12.16 ±0.53	-12.92 ±1.41	0.76 (-0.38, 1.90)	6.25	0.73 (-0.59, 2.05)	-13.97 ±3.69	-11.22 ±3.34	2.75 (-6.39, 0.88)	19.68	-0.77 (-1.85, 0.29)
Mean force (N)	1843.44 ±210.09	1808.64 ±285.63	34.80 (-346.21, 201.47)	1.88	-0.28 (-1.18, 0.61)	1386.51 ±111.71	1296.68 ±157.50	89.83 (-102.49, 210.81)	6.47	0.37 (-0.66, 1.42)
Mean velocity ($m \cdot s^{-1}$)	1.35 ±0.09	1.26 ±0.12	0.09 (-0.09, 0.15)	6.66	0.26 (-0.50, 1.04)	1.09 ±0.09	1.04 ±0.02	0.05 (-0.007, 0.14)	4.58	0.93 (-0.15, 2.02)
Mean power (W)	2380.04 ±255.64	2226.28 ±483.13	153.76 (-464.24, 393.29)	6.46	-0.08 (-0.98, 0.81)	1466.88 ±135.28	1327.52 ±156.03	139.36 (-35.40, 287.57)	9.50	0.82 (-0.25, 1.89)
Jump height (m)	0.33 ±0.04	0.29 ±0.04	0.04 (-0.04, 0.30)	12.12	0.23 (-0.74, 0.92)	0.22 ±0.03	0.21 ±0.02	0.01 (-0.01, 0.04)	4.54	0.46 (-0.58, 1.51)
Flight time (sec)	0.50 ±0.03	0.48 ±0.04	0.02 (-0.04, 0.05)	0.04	0.17 (-0.60, 0.96)	0.42 ±0.03	0.41 ±0.01	0.01 (-0.01, 0.03)	2.38	0.31 (-0.72, 1.35)
Take-off velocity ($m \cdot s^{-1}$)	2.52 ±0.17	2.40 ±0.16	0.12 (-0.17, 0.25)	4.76	0.43 (-0.68, 1.55)	2.06 ±0.16	2.01± 0.10	0.05 (-0.08, 0.20)	2.42	0.44 (-0.60, 1.49)

* $p \leq 0.05$, ** $p \leq 0.01$.

Given the significant differences reported for F-v characteristics, along with mean differences between other F-v and CMJ variables, it raises an interesting question as to what type of training each positional group should be involved in to improve mechanical performance based on the F-v characteristics? If force production at high velocities is a key requirement of field hockey players i.e., male attackers, strength and conditioning coaches should aim to support the mechanical characteristics of the position and prescribe exercises which develop or expose players to this quality such as assisted jumping (Markovic and Jaric, 2007) and sprinting actions (van den Tillaar, 2021). Whereas, if force production at low velocities is a characteristic of positional play i.e., female attackers, then exercises which require the player to express force at a slower velocity such as resisted sprint training (Morin et al., 2016) or back squat (Cormie et al., 2010) at higher percentages of one repetition maximum, would be useful to prepare for the positional demands of gameplay. Similar studies aimed at improving jump performance, have demonstrated individualized training based on F-v characteristics was attributed to significant changes in the performance outcome compared with a non-individualized, traditional resistance training approach (Escobar-Álvarez et al., 2020; Jiménez-Reyes et al., 2016; 2018b).

Table 5. Descriptive statistics and mean differences between sexes across all loads in force-velocity and countermovement jump variables.

Variable	Male	Female	Mean difference (±95%CL)	Mean % difference	ES (90% CI)
Absolute F_0 (N)	3082.33 ± 392.77	2196.10 ± 321.84	886.23 (629.69, 1142.75)	28.75***	2.74 (1.53, 3.41)
Relative F_0 (N·kg^{-1})	40.16 ± 3.70	34.01 ± 4.60	6.15 (3.19, 9.11)	15.31***	1.46 (0.66, 2.26)
Theoretical maximal v_0 (m·s^{-1})	3.20 ± 0.21	2.79 ± 0.45	0.41 (0.15, 0.66)	12.81***	1.13 (0.37, 1.90)
Absolute P_{MAX} (W)	2477.01 ± 382.55	1516.01 ± 224.37	961.00 (733.85, 1188.13)	38.79***	3.08 (2.03, 4.14)
Relative P_{MAX} (W·kg^{-1})	32.28 ± 4.31	23.45 ± 3.03	8.83 (6.15, 11.50)	27.35***	2.38 (1.45, 3.31)
Absolute S_{FV} (N·s^{-1}·m^{-1})	-960.85 ± 122.43	-785.00 ± 122.43	-175.85 (-292.56, 7.66)	18.30	-0.67 (-1.40, 0.05)
Relative S_{FV} (N·s^{-1}·m^{-1}·kg^{-1})	-12.52 ± 1.15	-12.15 ± 1.64	-0.37 (-1.82, 2.10)	2.95	0.04 (-0.66, 0.76)
Mean force (N)	1837.09 ± 273.79	1335.04 ± 173.18	502.05 (409.75, 594.34)	27.32***	2.20 (1.70, 2.71)
Mean velocity (m·s^{-1})	1.29 ± 0.18	1.05 ± 0.14	0.24 (0.16, 0.30)	18.60***	1.39 (0.95, 1.84)
Mean power (W)	2356.10 ± 384.07	1399.83 ± 188.64	956.27 (833.71, 1078.83)	40.58***	3.19 (2.58, 3.79)
Jump height (m)	0.31 ± 0.08	0.21 ± 0.04	0.09 (0.06, 0.13)	31.40***	1.10 (0.67, 1.52)
Flight time (sec)	0.49 ± 0.07	0.41 ± 0.04	0.08 (0.05, 0.11)	17.06***	1.36 (0.92, 1.79)
Take-off velocity (m·s^{-1})	2.46 ± 0.33	2.03 ± 0.23	0.43 (0.30, 0.53)	17.47***	1.48 (1.04, 1.93)

* $p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$, CL: confidence limits, ES: effect size, CI: confidence interval

Further to our first hypothesis, despite not achieving significance ($p \geq 0.07$), large mean differences in relative P_{MAX} (6.96 - 10.61%) were evident between positional groups (Table 4 and Figure 4). Previous research (Marcote-Pequeño et al., 2018) with other team sport athletes has highlighted maximal power in jumping (r = 0.84) and sprinting (r = 0.99) (Samozino et al., 2021) actions strongly correlated with its associated performance outcome, which is supported in this study by small differences in jump height. However, the mechanisms driving P_{MAX} characteristics appear to differ between sexes due to different combinations of force and velocity. Correlation coefficients between relative P_{MAX} and jump height for male ($r \geq 0.68$) and female ($r \geq -0.71$) positional groups (Figure 3) are similar to previous studies (Linthorne, 2021), however greater relative P_{MAX} values are evident in both attacking groups and would seem advantageous during short sprint actions on the field (i.e., acceleration actions). Previous findings (Samozino et al., 2021) support this where it is highlighted when attempting to improve maximal external power during sprinting, relative horizontal F_0 is of greater importance to sprint efforts <15-meters, i.e., force-oriented profile, whereas sprint efforts which exceed 15-meters are more reliant on v_0, i.e., velocity-oriented, which appears to be reflected in position-specific time motion analysis. Although female positional groups reported F-v characteristics which differ from their male counterparts, this may be explained through differences in tactics, technical abilities and overall skill level of the players as this has been shown to influence mechanical demands (van der Merwe and Haggie, 2019). This is an interesting finding for practitioners and compared to solely using time-motion analysis to understand and quantify the on-field game demands of sex and positional groups in field hockey, it may identify a new approach for individualizing training to improve P_{MAX} based on F-v characteristics.

Regarding our second hypothesis, we aimed to determine and compare the vertical F-v profile between men and women competing at the same level in club field hockey. In line with literature regarding sex differences and mechanical variables (Garhammer, 1991; Kraemer and Ratamess, 2004; Thomas et al., 2007), our results demonstrate males showed an overall more enhanced F-v profile due to higher values of both relative F_0 and v_0 (Figure 4: A), plus showed significantly superior CMJ variables at the same loads relative to bodyweight. When comparing sexes, large effect sizes were reported for absolute F_0 and P_{MAX} (Figure 5) which were likely due to musculotendinous structural characteristics and differences between sex (Komi, 1984; Laffaye et al., 2014). Although specific to sprint F-v characteristics, previous comparisons between males and females in soccer, a similar field sport, found the ability to produce force at high velocities i.e., v_0, was a limiting factor for female subjects (Jiménez-Reyes et al., 2018a). Furthermore, studies on high level sprint athletes identified significant differences in sprint mechanical properties (15 - 46%, ES $\geq$ 1.98, $p \leq 0.01$), with greater differences observed for v_0 than F_0 between males and females, along with moderate correlations evident between lower limb muscle and sprint outcomes (Nuell et al., 2019). Differences in force-time characteristics between sexes during the CMJ has also previously been shown due to higher relative peak concentric force, concentric impulse and eccentric rate of force-development, therefore leading to increased vertical velocity at take-off; the key determinant in jump height (McMahon et al., 2017). These findings were supported in this study with males demonstrating a 23.3% greater take-off velocity compared to females. It has been proposed changes to negative centre of mass displacement (i.e., countermovement squat depth) between sexes as a key determinant of CMJ performance (McMahon et al., 2017). Despite not reporting all kinematic jump variables, as it was not the primary focus of this study, structural differences including segmental lengths and muscle volumes may further explain sex differences between F-v profiles, however force-time characteristics are proposed to be important also (McMahon et al., 2017; Nuell et al., 2019).

When analyzing the performance outcome between sexes, male subjects displayed a 31% mean difference in jump height compared to females, which is a similar difference to previous studies (25 - 33% difference) and supported in the data due to higher relative vertical ground reaction forces (Haugen et al., 2020; Laffaye et al., 2014). Differences observed between F-v characteristics and jump height highlights a greater reliance on relative F_0 in male subjects ($r \geq 0.75$). These observations were not made with female subjects ($r \geq -0.07$) highlighting potential sex-differences in jump strategy as external load increases (McMahon et al., 2017), while also inferring training design to increase P_{MAX} between groups would likely be sex-specific. Lower correlations between jump height and P_{MAX} as observed in the female cohort may also be explained in reference to variations in countermovement depth, one's own body mass independent of strength levels and heterogenous individual F-v profiles (Jaric, 2015; Morin et al., 2019). Furthermore, it has been reported approximately only 40 - 80% of differences in jump performance can be explained via differences in P_{MAX}, suggesting the results in this study may not be atypical (Samozino, 2018). The training history, ability level and age of subjects in this study may also present potential interactions with covariant variables, therefore creating a level of uncertainty when attempting to link neuromuscular capability with jump performance (Samozino, 2018). Therefore, this further supports the utility of using a F-v profile to understand mechanical variables rather than performance outcomes such as jump height to infer mechanical characteristics of athletes.

In other movement tasks, the linear relationship between force and velocity (i.e., S_{FV}) has been shown to be more individual (Haugen et al., 2019) than sport specific suggesting mechanical demands at each position group in field hockey may not fully explain the underpinning mechanisms of jump performance. Although S_{FV} differences were evident between attackers and defenders (i.e., force or velocity oriented), it may also be the case of athletes or coaches selecting positions on the field which match their biomechanical strengths and avoiding positions which may highlight a weakness. For example, male athletes who can express force at low velocities but limited in their ability to express force at high velocities may choose to position themselves in the defensive half of the field to ensure their biomechanical limitations match the lower demand of high intensity actions at this end of the pitch. Nonetheless, irrespective of the initial S_{FV}, interventional approaches in jump and sprint studies have highlighted the adaptability of the S_{FV} to respond to targeted training i.e., high force training addressing a force deficit (Jiménez-Reyes et al., 2016; Jiménez-Reyes et al., 2019; Lahti et al., 2020), suggesting that individual F-v characteristics should always be a consideration when determining training interventions.

Overall, there were several strengths to this cross-sectional study. Firstly, there is a paucity of research investigating mechanical demands within field hockey and therefore this study adds new reference data for practitioners. Secondly, despite attackers and defenders essentially performing the same tasks in both men's and women's field hockey (i.e., moving the ball forward for an attacking play on goal, or defending the opposing team's attack on goal), the findings suggest physical preparation coaches working with male and female players should design training programmes to reflect the different mechanical demands required in each field position. Finally, this study provides a suggested training design framework for attackers and defenders to focus on during their preseason period, plus also highlights the utility of vertical F-v profiling within this field hockey context.

There were some limitations in the current study identified by the authors. Force-velocity profiles created using only three incremental loads (bodyweight + two external loads) and the proximity of the loads in reference to each other and the axis intercepts (F_0, v_0) may limit the findings. Although the mechanical variables in the three-point loading protocol used this study were shown to be reliable between sexes (ICC: 0.87 - 0.97, CV% 2.7 - 5.7), the highest external added load, body mass + 50% externally added mass relative to body mass, was likely not distal enough across the F-v spectrum to provide a true representation of F_0 capabilities. Concerns with linear regression models using moderate forces to predict characteristics at high forces have previously been raised (Alcazar et al., 2019). Despite this, external loads in this study were selected due the ability level and resistance training competency of the subjects, plus provide a safer expression of force for subjects. Furthermore, if a greater duration of time was allocated to testing, a multiple-point F-v assessment could have been performed therefore providing more distal F-v characteristics (Garcia Ramos and Jaric, 2017; Pérez-Castilla et al., 2021). Secondly, the cross-sectional approach and competition level of subjects used in this study may hinder the transfer of findings to higher level field hockey athletes. Although inferences were made between time-motion analysis of elite level players and F-v characteristics of club-based players in this study, exploration of F-v profiles in national or international level field hockey athletes and creating individualized training interventions to optimize mechanical characteristics for specific positional groups would further research in the field. One final limitation may be sample size of the study, which may reduce statistical power for some variables and increase the margin of error, which can effect results or interpretation to higher level field hockey athletes.

Conclusion

Understanding the relationships between sex and positional demands in field hockey athletes appears to identify vertical F-v profiles can provide new insight about individualizing strength and conditioning programs based on mechanical characteristics. Based upon the findings of the present study, when analyzed by positional group, male attackers displayed a more 'velocity-oriented' profile compared to defenders, whereas female attackers displayed a more 'force-oriented' profile in comparison to defenders. The significant differences evident between male players suggests the positional F-v requirements of attackers is their ability to express force at high velocities, however between female positional groups, the ability to produce and express force at low velocities differentiates attackers from defenders, thereby highlighting the dominant mechanical characteristic underpinning expression of maximal power at each position. Between sexes, males displayed an overall more enhanced F-v profile likely due to musculotendinous and structural differences. Overall, we recommend practitioners working with field hockey players to utilize a range of loads and exercises which span the F-v continuum however account for specific F-v differences between positional group and sex within the training program. We conclude that the F-v profile assessment is acceptable to distinguish between positional group and sex in club-based field hockey athletes and provides guidance for training interventions to enhance mechanical characteristics.

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Key points

- Significant force-velocity differences exist between attackers and defenders within club-based field hockey players
- When analyzed by positional group, male attackers displayed a more 'velocity-oriented' profile compared to defenders, whereas female attackers displayed a more 'force-oriented' profile in comparison to defenders.
- The significant differences evident between players suggests the positional force-velocity requirements of each position requires specific training
- F-v profile assessment is acceptable to distinguish between positional group and sex in club-based field hockey athletes and provides guidance for training interventions to enhance mechanical characteristics.

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