

**DETERMINING THE RELATIONSHIP BETWEEN RUN-UP AND TAKE-OFF
CHARACTERISTICS AND PERFORMANCE IN TOP LEVEL POLE VAULTERS
USING DEEP LEARNING BASED MARKERLESS MOTION CAPTURE**

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TIIVISTELMÄ

Outinen, P. 2021. Huippuseiväshyppääjien vauhdinjuoksun, sekä maastalähdön ominaisuuksien ja suorituskyvyn välisen yhteyden selvittäminen käyttäen syvään oppimiseen perustuvaa ”markerless” liikkeen tunnistusta. Liikuntatieteellinen tiedekunta, Jyväskylän yliopisto, Biomekaniikan pro gradu -tutkielma, 61 s, 2 liitettä.

Tämän tutkimuksen tarkoituksena oli selvittää mitkä tekijät juoksun ja maastalähdön vaiheista määrittävät vauhdinjuoksun aikaisen energian tehokkaan siirron hyppykorkeudeksi ja miten nämä eroavat miesten ja naisten välillä. Aiemmin käytetyt seiväshypyn tutkimusmenetelmät ovat olleet hitaita toteuttaa ja rajoittaneet muun muassa tutkittavien henkilöiden määrää, jota pyrittiin tämän tutkimuksen menetelmävalinnoilla korjaamaan.

Tutkimuksessa analysoitiin 2d-liikeanalyysillä Birminghamin vuoden 2018 hallimaailmanmestaruuskilpailuiden seiväshyppääjien (n=26) parhaiden suoritusten vauhdinjuoksua ja maastalähtöä. Osallistujista 15 oli miehiä ja 11 naisia. Hyppääjien suoritukset kuvattiin kahdesta kuvakulmasta, joista liikedata tallennettiin neuroverkkopohjaisella kuvantunnistusmenetelmällä ja suoralla lineaarisella muunnoksella. Menetelmän toimivuus varmistettiin muun muassa laskemalla samasta kilpailusta aiemmin tehdyn tutkimuksen muuttujia tämän tutkimuksen vastaaviin muuttujiin. Vauhdinjuoksusta ja maastalähdöstä laskettiin 12 muuttujaa, sekä yksi suorituskyky muuttujia analysointia varten. Tutkimuksessa tarkasteltiin muuttujien välisiä korrelaatioita, miesten ja naisten tekniikan eroavaisuuksia sekä mallinnettiin muuttujien yhteisvaikutusta suorituskyky muuttujaan.

Neljä keskenään korreloivaa maastalähdön muuttujaa yhdistettiin kuvaamaan maastalähdön tekniikkaa. Tekniikkamuuttujia sai suuria arvoja, kun seipäseen törmäys tapahtui heti ponnistuskontaktin alkaessa (aikainen törmäys), jolloin muun muassa yläkäden otekohta oli selkeästi ponnistusjalan kärjen takana, seiväs taipui voimakkaasti maassa ja massakeskipiste nousi ylöspäin. Vastaavasti pieniä arvoja muuttujia sai, kun törmäys tapahtui kontaktin lopussa (myöhäinen törmäys), jolloin yläkäden otekohta oli ponnistusjalan kärjen etupuolella, seiväs ei juurikaan taipunut maastalähdössä ja massakeskipiste pysyi korkeudeltaan paikallaan. Energiansiirtokyky heikkeni juoksunopeuden kasvaessa sekä miehillä ($r = -0,779$, $p < 0.01$) että naisilla ($r = -0,864$, $p < 0.01$), sekä miehillä oli keskimääräisesti huonompi energiansiirto kuin naisilla (-3 %, $t (-2,235)$, $p < 0,05$). Yleisessä energiansiirron regressiomallissa ($R^2 = 0.639$) suurin positiivinen vaikutus tuli maastalähdön horisontaalisen nopeuden säilytyksestä ($b = 0,728$) ja aikaisen törmäyksen tekniikasta ($b=0,662$). Miesten regressiomallin ($R^2 = 0.752$) kertoimet vastasivat pääosin yleistä mallia, mutta painotti enemmän maastalähdön tekniikkaa ($b = 0,834$), kuin nopeuden säilymistä ($b = 0,799$). Naisilla malli ($R^2 = 0.984$) painotti eniten juoksun muuttujien negatiivista vaikutusta (askelpituus $b = -1,673$ ja askeltiheys $b = -1,280$).

Naisten keskimääräisesti parempaa energiansiirtoa selittää mahdollisesti heidän käyttämänsä matalampi suhteellinen otekorkeus, joka voisi tarjota paremmat edellytykset seipään ojentumisvaiheen energianpalautukseen. Energiansiirto heikkenee nopeuden kasvaessa, mutta energiansiirtoon voidaan vaikuttaa positiivisesti pyrkimällä mahdollisimman aikaiseen törmäykseen ponnistuskontaktin aikana, jolla vielä säilytetään horisontaalinen nopeus mahdollisimman hyvin. Naisten osalta energiansiirto heikkenee teknisistä valinnoista huolimatta nopeuden kasvaessa, mutta miehillä tätä ei havaittu. Syynä tälle voisi olla, että miesten suurempi nopeus heikentää kykyä suorittaa energiansiirrolle positiivista maastalähdön tekniikkaa. Tämän pohjalta voisi päätellä, että tulevaisuudessa ylivertainen urheilija voisi olla sellainen, joka pystyy suuresta nopeudesta huolimatta suorittamaan hitaampiin urheilijoihin verrattavan tehokkaan maastalähdön.

Asiasanat: seiväshyppy, biomekaaninen analyysi, markerless, syväoppiminen

ABSTRACT

Outinen, P. 2021. Determining the relationship between run-up and take-off characteristics and performance in top level pole vaulters using deep learning based markerless motion capture, Faculty of Sports Science, University of Jyväskylä, Master's thesis in biomechanics, 61 pp., 2 appendices.

The purpose of this study was to determine which factors from run-up and take-off phases determine effective energy conversion from run-up to a cleared height and how these factors differ between men and women. Methods used in pole vault studies in the past have been slow to implement which has led to a reduced number of participants used in studies. Method choices in this study are aimed to solve the problems from methods used in previous studies.

2d-motion analysis was used in this study to analyse run-up and take-off properties of pole vaulters (n=26) best jump from 2018 Birmingham world indoor championships. 15 of the participants were men and 11 were women. The performances of the athletes were filmed from two angles from which the motion data was created using neural network-based image recognition and direct linear transformation. The functionality of the method was ensured by comparing corresponding variable values from this method to the variable values used in previous study from the same competition. 12 variables from run-up and take-off were calculated as well as one performance variable for the analysis. Correlations between variables, differences between men and women, and combined effect of the variables to the performance were explored.

Four correlated take-off variables were combined to describe the take-off technique. The variable had high values when athlete performed early plant during take-off contact, top grip was behind take-off foot-tip, pole bended heavily before contact take-off and centre of gravity rose upwards. Correspondingly small values were obtained when the late plant was performed during the take-off contact, top grip was on the front of the take-off foot-tip, pole barely bending before contact take-off and centre of gravity remained similar in vertical position. Energy conversion decreased as the athlete's velocity increased both in men ($r = -0,779$, $p < 0.01$) and women ($r = -0,864$, $p < 0.01$), and men had on average worse energy conversion (-3 %, $t (-2,235)$, $p < 0,05$). In the general regression model ($R^2 = 0.639$), the largest positive effect came from the preservation of the horizontal velocity during take-off ($b = 0,728$) and take-off technique that favoured early plant ($b=0,662$). Men's models ($R^2 = 0.752$) coefficients corresponded to the general model but favoured more the similar take-off technique ($b = 0,834$) than the preservation of velocity ($b = 0,799$). In women, the model ($R^2 = 0.984$) emphasized the most the negative effect of running variables (step length $b = -1,673$ and step rate $b = -1,280$).

On average better energy conversion of women could be explained by the use of lower relative grip height which could provide better conditions to energy return in the pole straightening phase. Energy conversion decreases with increasing velocity but the energy conversion could be positively affected by striving for an earlier plant which still maintains as much as the horizontal velocity as possible. For women, energy conversion decreases with increasing speed regardless of the technical choices, but this was not observed in men. Reason for this could be that the higher velocities impair the ability to perform beneficial take-off technique for the energy conversion. Based on this, it could be concluded that in the future, a superior athlete might be the one that could perform despite high velocity an effective take-off comparable to slower athletes.

Key words: pole vault, biomechanical analysis, markerless, deep learning

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1 INTRODUCTION

Pole vault as a competition event has developed from the horizontal distance jumping in 16th century to a modern vertical jumping starting in the 1850s. After that, vaulters have used poles with different materials and varying techniques to reach new heights. (World Athletics n.d.a.) Under the current competition rules, vaulter jumps across the crossbar using a pole that can be any material as long as its uniform and smooth. Vaulter can use any other technique than climbing and must go over the bar without any efforts to prevent the crossbar from dropping. (World Athletics 2019.)

The world record of the pole vault has increased about 3.5 cm per year from the 1890s to the start of the second world war, which levelled off the progression for almost 20 years. The improvements continued after 1961 with a rapid increase (7.2 cm per year) due to introduction of bending glass fibre poles. Before that, athletes used bamboo, aluminium, or steel poles which were compromised by either durability or elastic properties compared to glass fibre poles. (Haake 2009.) World record reached its maximum in 1994 when Sergey Bubka cleared the world outdoor record of 6.14 meters, which was unbeaten for 20 years (Haake 2009; World Athletics n.d.b).

Both men's and women's world record growths have plateaued for over 10 years which can be seen in figure 1. Women's current world record holder is Yelena Isinbayeva with 5.06 m from 2009 (World Athletics n.d.c). Renaud Lavillenie broke Sergey Bubkas world record just before its 20th birthday in 2014 which was next passed in 2020 by Armand Duplantis and is currently set to 6.18 m (World Athletics n.d.b). Next world record holder after Bubka was thought to be slightly taller, faster, and stronger version of Bubka with a similar technical model. Lavillenie and Duplantis proved these predictions wrong with a seemingly smaller appearance and different technical model. Although there is a lot of research and knowledge about pole vaulting, new wave of pole vaulters might bring new insights on how old technical and mechanical models can be modified to a better performance.

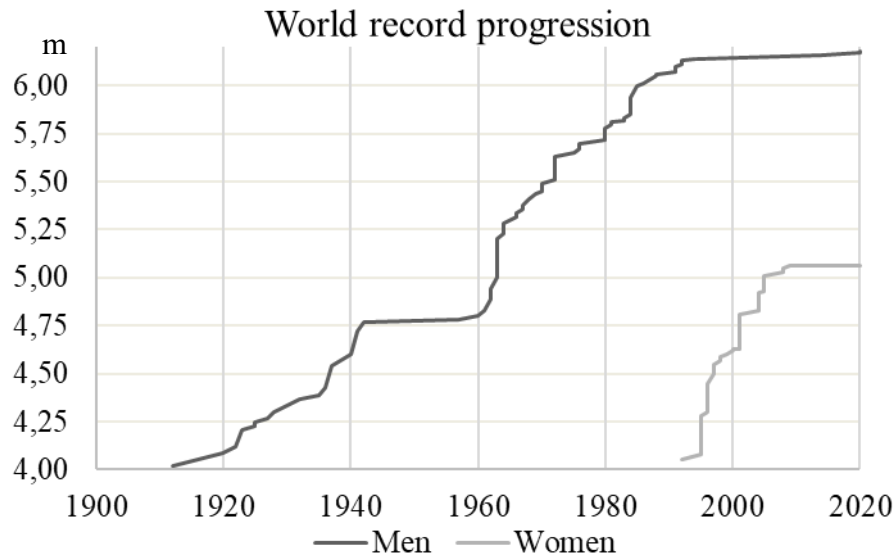


FIGURE 1. World record progression for men and women (World Athletics n.d.b; World Athletics n.d.c.).

Women’s pole vault is a relatively young competition compared to men’s pole vault and women’s technique is known to be slightly different than men’s (Schade et al. 2004; Cassirame et al. 2017). 1992 was first year that official women’s world record has been recognised by athletics federation (World Athletics n.d.c) and Sydney 2000 Olympics were first competition to introduce women’s pole vault as an Olympic event (Schade et al. 2004). Women’s world record saw a rapid growth at the beginning of its time, but nobody has been able to improve the record after 2009 (World Athletics n.d.c). Focusing research and efforts to developing women’s technique separately to men might lead into further improvements to the world record.

Most of the pole vault studies in real-world scenarios include kinematic analysis from manually digitised videos, and some include direct measurements like forces or velocities. This setup can be used to provide an accurate presentation on how the pole and vaulter behave during the jump. The biggest weakness has been the placement of measuring devices on the track and the labour cost of manual digitization, which restricts the amount of data collected and analysed. With modern technology, the data could be easier to collect which helps to do more extensive research in the future.

2 POLE VAULT PHASES

This chapter provides the basics of the modern-day pole vault technique (Figure 2) and the vocabulary used to describe it. Angulo-Kinzler et al. (1994) divided pole vault into four phases in their biomechanical analysis which are run-up phase, take-off phase, pole support phase and free flight phase. This four-part division is used as a backbone in this study to clarify the course of execution. In addition to this basic division, pole support phase can be further divided into pole bending and pole straightening phases to differentiate vaulter-pole energy transformations during the vault (Arampatzis et al. 1997). Illustration of the pole vault execution and rough division to phases are in Figure 2. More detailed division will be described in the following sections.

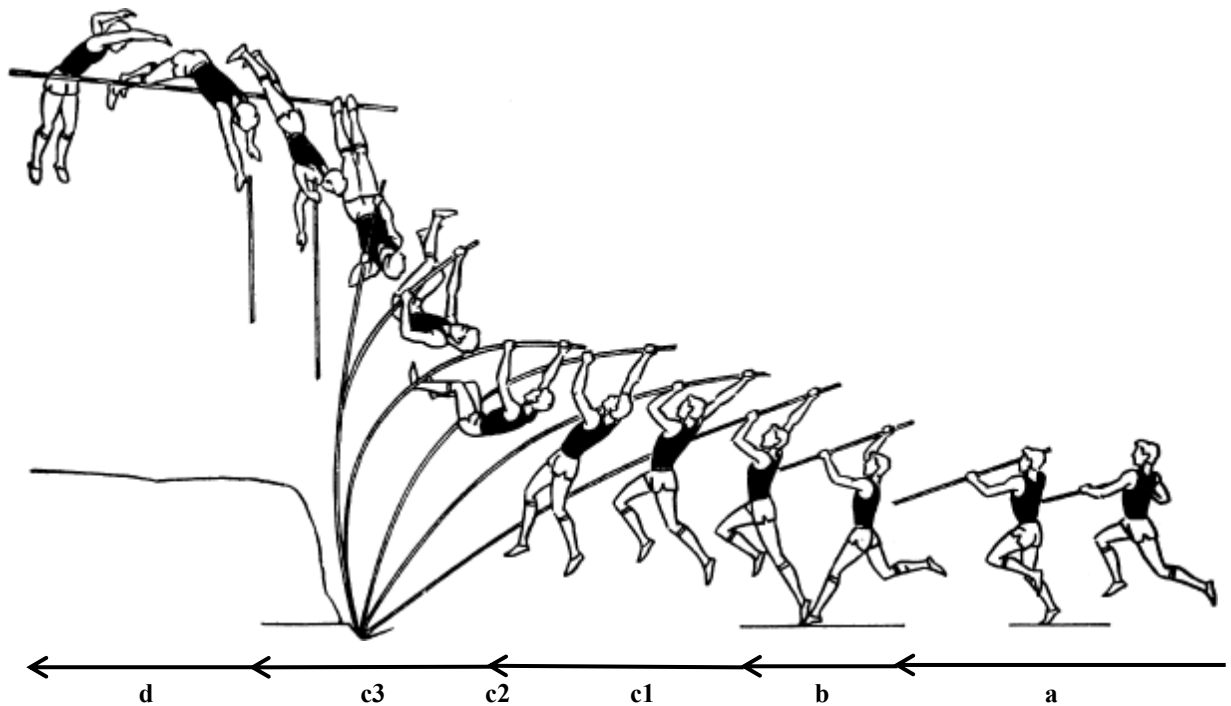


FIGURE 2. a. Run-up phase, b. Take-off phase, c. Pole support phase where c1. Pole bending phase, c2. Maximum pole bend position and c3. Pole straightening phase and d. Free flight phase. Pole vault image from Linthorne (2000) with added indicators of phases according to Angulo-Kinzler et al. (1994) and Arampatzis et al. (1997).

2.1 Run-up phase

Run-up phase starts from the beginning of the run and ends until the touchdown of the last contact. Run-up includes production of horizontal velocity, preparing optimal body position to the take-off and gradual lowering of the pole bottom to the planting box (Angulo-Kinzler et al. 1994).

The main goal is to achieve the highest possible horizontal velocity (Angulo-Kinzler et al. 1994), but some vaulters regulate their running to achieve better take-off position possibly at the expense of horizontal velocity (Needham et al. 2018). It has also been noted that running with the pole cannot be as fast as running without the pole which is due to the power output deficit caused by carrying the pole (Angulo-Kinzler et al. 1994; Frère et al. 2017).

2.2 Take-off phase

Take-off phase starts from the touchdown of the last contact and ends at the end of the contact. Take-off also includes the pole plant where pole bottom hits the end of the planting box. Before the pole plant, vaulter raises his/her arms above the head and prepares the body for the impact. (Angulo-Kinzler et al. 1994.) Planting box is a platform that descends 20 cm from the runway level and ends with an end plate which stops the movement of the pole. Figure 3 shows the shape and measures of the official planting box used in competitions. (World Athletics 2019.)

The purpose of the take-off is to create smooth transfer from run-up to pole support phase while minimizing the loss of energy from the run-up phase. Important variables that affect the take-off energy transfer are distance from top hand to pole bottom (i.e. grip height), horizontal distance from top hand and take-off foot (i.e. take off position), angle of resultant velocity in relation to horizontal plane (i.e. take-off angle), force needed to bend the pole (i.e. pole stiffness) and distance between top and bottom hand (i.e. grip width) (Angulo-Kinzler et al. 1994; Linthorne 2000).

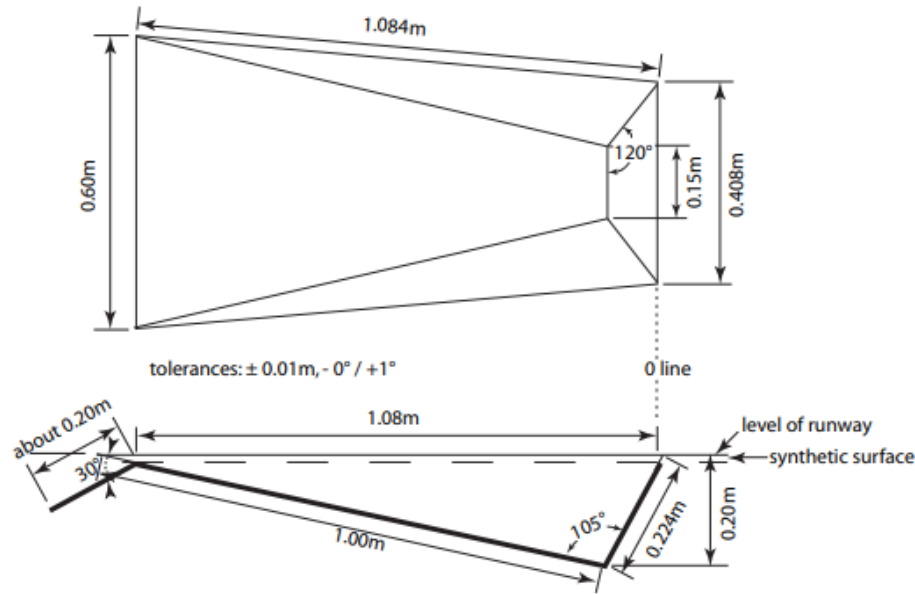


FIGURE 3. Official measures for the planting box. (Image from World Athletics 2019).

2.3 Pole support phase

Pole support phase starts at the end of take-off and ends when vaulter has released both hands from the pole (i.e. pole release). Athletes only contact with ground is through the pole in this phase, therefore the name pole support phase. (Angulo-Kinzler et al. 1994.) Phase can be further divided into pole bending and pole straightening phases. In the pole bending phase, pole stores vaulter's kinetic energy to strain energy, and in the pole straightening phase, pole releases the energy back to the vaulter as vertical kinetic energy. Phases are divided by maximum pole bend position when amount of pole bend and strain energy reaches maximum values. (Arampatzis et al. 1997.)

After the take-off, the pole rotates to the vertical around its axis which is in the planting box using kinetic energy from the vaulter. Vaulter utilizes his/her kinetic energy to rotate (i.e. swing) on the opposite way to the pole's rotation to raise and move the centre of gravity to the other side of the pole. Just after the swing, vaulter straightens and pulls himself higher while turning in a way that crossbar is approached legs and ventral side first. (Angulo-Kinzler et al. 1994.)

Utilizing modern vaulting poles' elastic properties, vaulter can add strain energy to the pole in the pole bending phase by actively bending the pole. In the pole straightening phase, vaulter can actively pull itself higher to gain more height to the vault. (Angulo-Kinzler et al. 1994; Morlier & Mensard 2007; Fukushima et al. 2014.) Sometimes term called “rock back” is used to describe the “rocking” motion at the end of the swing and just before the pull up. During the rock back, body is positioned rapidly close to the pole to better receive the energy release from the pole. This can be noticed as an increase in vertical force from the planting box. (Angulo-Kinzler et al. 1994; Morlier & Cid 1996; Schade et al. 2000.)

2.4 Free flight phase

In the free flight phase, vaulter does not have any contact point to anything. Therefore, vaulter uses all the leftover kinetic energy and angular momentum to cross the bar in a parabolic shaped flight path. (Angulo-Kinzler et al. 1994.) Beginners and some women are not able to increase the centre of gravity in free flight phase due to lack of vertical velocity at the end of the pole straightening. If this is the case, then vaulter achieves its highest potential energy before the free flight phase. (Schade et al. 2004.)

Vaulters choice of grip height and pole stiffness changes vaulters position and flight path in the free flight phase (Linthorne 2000). To manage these changes, vaulter can choose the horizontal position of the crossbar between the end of the planting box (i.e. zero line) and a point 80 cm further towards the landing area. The number of changes is not limited during the competition. (World Athletics 2019.)

Method of calculating height of the jump is determined by grip height and height that vaulter can jump above the top hand (i.e. push height). Grip height does not directly determine the jump height, because the planting box reduces 20cm from it in which case we speak about effective grip height. (Linthorne 2000.) This can be used as a guide to see if increased height is due to increased grip height or better technique to allow higher push height.

3 POLE VAULT MECHANICS

This chapter describes the mechanics that are involved in pole vaulting and ways to influence on them. The term mechanical energy applies only to the energy of the vaulter's body, which includes potential energy, translational kinetic energy, and rotational kinetic energy (Schade et al. 2000). Simplified from Schade et al. (2000), total mechanical energy of the vaulter can be calculated as follows:

$$E_{mech} = \sum_{i=1}^n m_i g h_i + \sum_{i=1}^n \frac{1}{2} m_i v_i^2 + \sum_{i=1}^n \frac{1}{2} \Theta_i \omega_i^2$$

where m_i is the mass, h_i is the centre of gravity height, v_i is the resultant velocity, Θ_i is the moment of inertia and ω_i is the angular velocity of the i th segment of the n amount of body parts. In addition to mechanical energy, bending pole stores strain energy which is caused by compressive force and bending moment and can be calculated as follows:

$$E_{pole} = \int F_p \cdot dr + \int M \cdot d\beta$$

where F_p is the force produced in direction of pole deformation, r is distance from top hand to pole bottom (i.e. chord), M is the bending moment produced by both hands and β is the angle between pole tangent at top grip and pole chord (Arampatzis et al. 2004).

Figure 4 shows the typical curves how the energy state changes during the jump. The following sections of this chapter describe further how energy parameters changes over the course of the jump and how an athlete can influence to them to gain better performance.

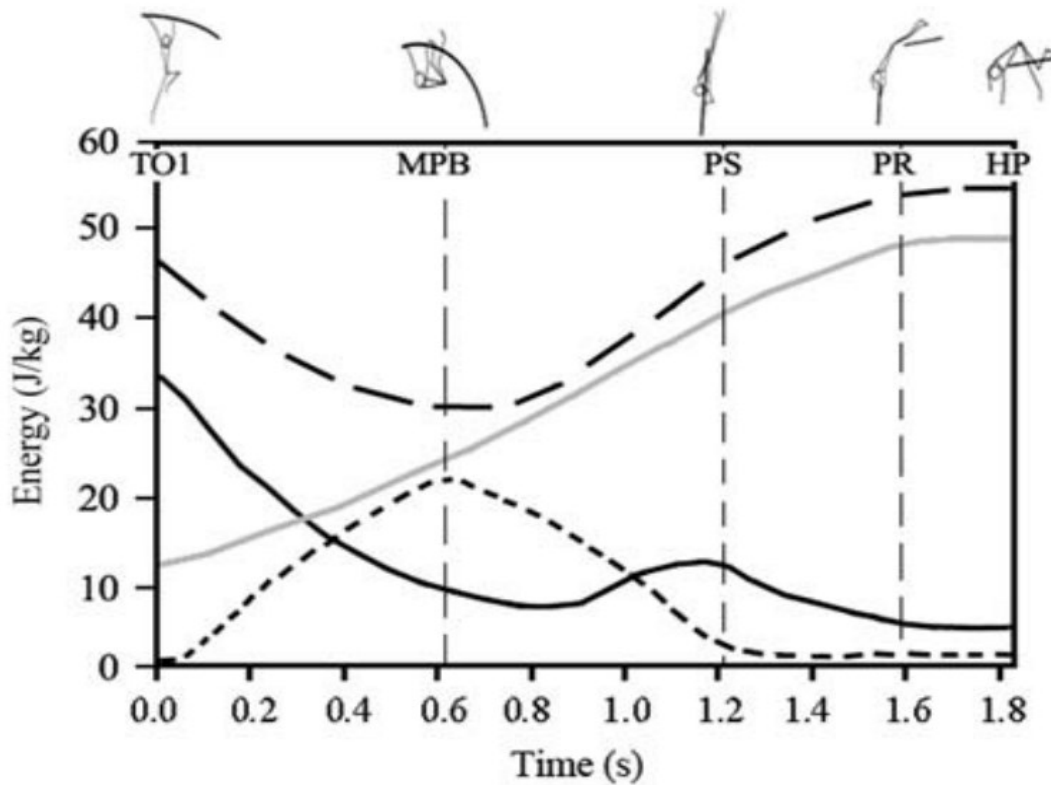


FIGURE 4. Typical curves of the development of energy parameters during the jump where are kinetic energy (black line), potential energy (grey line), strain energy of the pole (dotted line) and total mechanical energy of the vaulter (dashed line). (Figure from Frère et al. 2012).

3.1 Translational kinetic energy

Vaulter develops needed horizontal velocity and momentum in other words initial kinetic energy by running during the run-up phase (Angulo-Kinzler et al. 1994). High horizontal kinetic energy at run-up and take-off is one of the main performance determining factors, but only when combined with effective technique in later parts of the jump (Angulo-Kinzler et al. 1994; Cassirame et al. 2017). Kinetic energy is most affected by energy loss at take-off and horizontal kinetic energy transfer to vertical.

At take-off, the take-off angle and pole stiffness determine how much kinetic energy is lost. Firstly, the take-off angle determines how much horizontal kinetic energy is changed to the vertical at take-off. With greater take-off angles, vaulter must produce some force in the

opposite direction to change his/her momentum more vertical thus leading into some energy loss. Second loss of kinetic energy comes from the reaction force of the pole plant. Force from the plant through the pole exceeds muscular forces that try to maintain body position leading into deformation of the body position and kinetic energy loss as heat into the vaulter's muscles. In practice, larger take off angle results in a greater loss of horizontal kinetic energy, and stiffer poles adds to the loss as well due to the larger reaction force. (Linthorne 2000.) For the experienced vaulters, energy loss comes mainly from jumping motion, but for beginners the main source of energy loss is the reaction force of the pole plant (Schade et al. 2012). To prepare for the kinetic energy loss at take-off, vaulter should focus on maximising kinetic energy just before take-off and have upper body strength to receive the impact of the plant for the smooth transition to the pole support phase (Frère et al. 2010).

Translational kinetic energy includes horizontal and vertical kinetic energy and from the perspective of kinetic energy, the pole support phase's main purpose is to transfer horizontal kinetic energy to vertical through the strain energy of the pole. Velocity curves during the vault show that the main direction of travel is horizontal in pole bending phase and vertical in the pole straightening phase with the transition of main direction happening at maximum pole bend position. In the pole straightening phase, pole returns energy to the vaulter which increases vaulter's vertical velocity and vaulter can actively pull itself higher at this stage to add more vertical kinetic energy. This can be seen in Figure 4 as a slight bump in total kinetic energy before pole straightens. (Angulo-Kinzler et al. 1994; Frère et al. 2010.) After the pole straightens, vaulter reaches maximum vertical kinetic energy and has some horizontal kinetic energy left. Remaining of the vertical kinetic energy decreases after the pole straightens leading into the peak height and potential energy of the vaulter when it reaches zero. Because vaulter has no contact point after the pole release, horizontal velocity remains constant and is used to achieve the parabolic flight path to go over the crossbar. (Angulo-Kinzler et al. 1994.)

3.2 Strain energy of the pole

With modern flexible poles, pole stores part of vaulter's horizontal kinetic energy into strain energy and releases it back to vertical kinetic energy resulting an increase in potential energy

(Angulo-Kinzler et al. 1994). As seen on the Figure 4, pole's strain energy increases until the maximum pole bend position and decreases until the pole straightens. Compared to old stiff poles, advantage from flexible poles is the ability to use a lower take-off angle that minimises energy loss and allows more efficient kinetic energy transfer to the potential energy mainly due to efficient storing and releasing of the strain energy (Linthorne 2000), but also via ability to add strain energy by active bending of the pole (Morlier & Mesnard 2007).

The amount of poles strain energy is determined by bending moment and compressive force (Arampatzis et al. 2004) and is illustrated in Figure 5. Compressive force is the force produced in direction from the top hand to the planting box and is calculated as integral of force and pole chord length (Frère et al. 2010; Arampatzis et al. 2004). Bending moment is the total moment produced to bend the pole and is calculated as integral of the reaction force from the pole perpendicular to the pole chord, and angle between pole tangent at top hand and pole chord. Bending moment is transmitted through the plane defined by top and bottom hands. (Frère et al. 2010; Arampatzis et al. 2004; Morlier & Mesnard 2007)

With elastic poles, reaction force from the plant is smaller compared to stiff poles which allow vaulter to use lower take-off angle both resulting to less kinetic energy loss at take-off and more momentum to be utilized in the later parts of the jump (Linthorne 2000). With greater amount of kinetic energy to be utilized, the pole bending starts with the plant where vaulter's momentum creates compressive force that bends the pole which can be facilitated by pushing up against the pole with the bottom arm to create a stronger bending moment (Angulo-Kinzler et al. 1994). Vaulter can prolong the take-off contact to use ground as a point of support to increase the bending moment at take-off. By doing that, vaulter can resist the deformation of the body better and add energy to the pole before the end of the take-off contact. (Morlier and Mesnard 2007.)

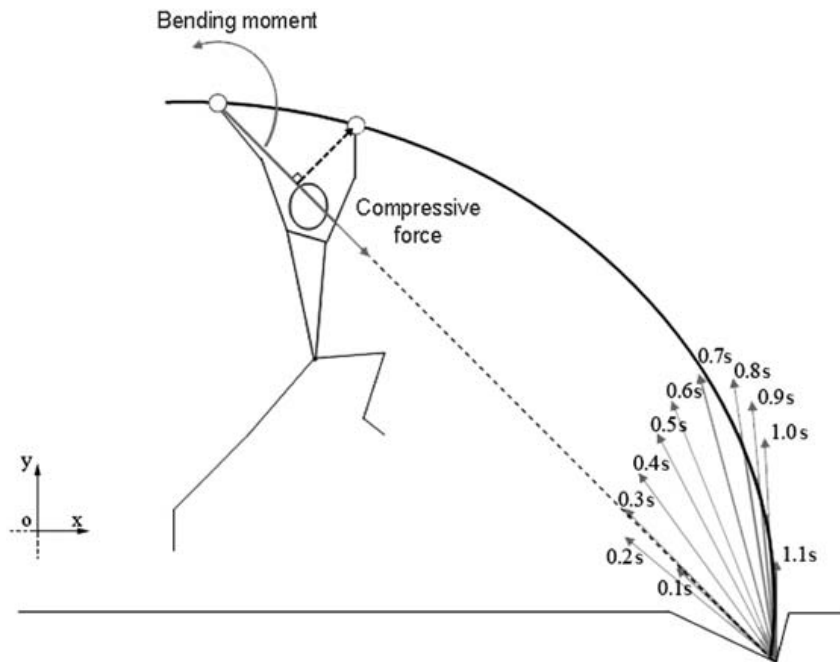


FIGURE 5. Compressive force and bending moment directions from the pole bending phase. At the bottom of the pole is the direction and magnitude of the reaction force from the planting box during the jump. Time values represent the time relative to the pole plant. (Image from Frère et al. 2010).

In the pole bending phase, vaulter can create significant bending moment to add additional strain energy to the pole using upper body muscles (Morlier & Mesnard 2007; Frère et al 2012). It has also been noticed that women bend poles sacrificing their mechanical energy to the compressive force, but men use more muscle force to create the bending moment to add energy to the jump (Schade et al. 2004). In the pole straightening phase, vaulter can pull itself higher and produce a negative bending moment to create larger vertical impulse to accelerate and add more vertical kinetic energy which leads to higher total energy and greater push height (Angulo-Kinzler et al. 1994; Fukushima et al. 2014). The energy gain from the take-off to the total energy at the end of the jump increases about 20% which is an indication of the additional energy produced by muscle work (Frère et al. 2012; Ekevad & Lundberg 1995).

3.3 Angular momentum

Angular momentum is a crucial part of successful vault mainly due to swing-up motion in the pole support phase. The torque generated by the pole to the vaulter after the take-off causes some of the kinetic energy to be transformed into rotational kinetic energy and therefore increases the angular momentum of the vaulter around the transversal axis. Angular momentum increases with minimal effort until the vaulter's centre of gravity passes poles chord, because then torque from the pole changes sign and starts to work against the swing. This happens usually just before maximum pole bend position and by tucking in vaulter can decrease its moment of inertia to increase angular velocity to finish the swing-up to a better position for receiving the energy from the pole (i.e. rock back). (Angulo-Kinzler et al. 1994.) This swing up motion can be seen in Figure 6 as the largest descending and ascending graph.

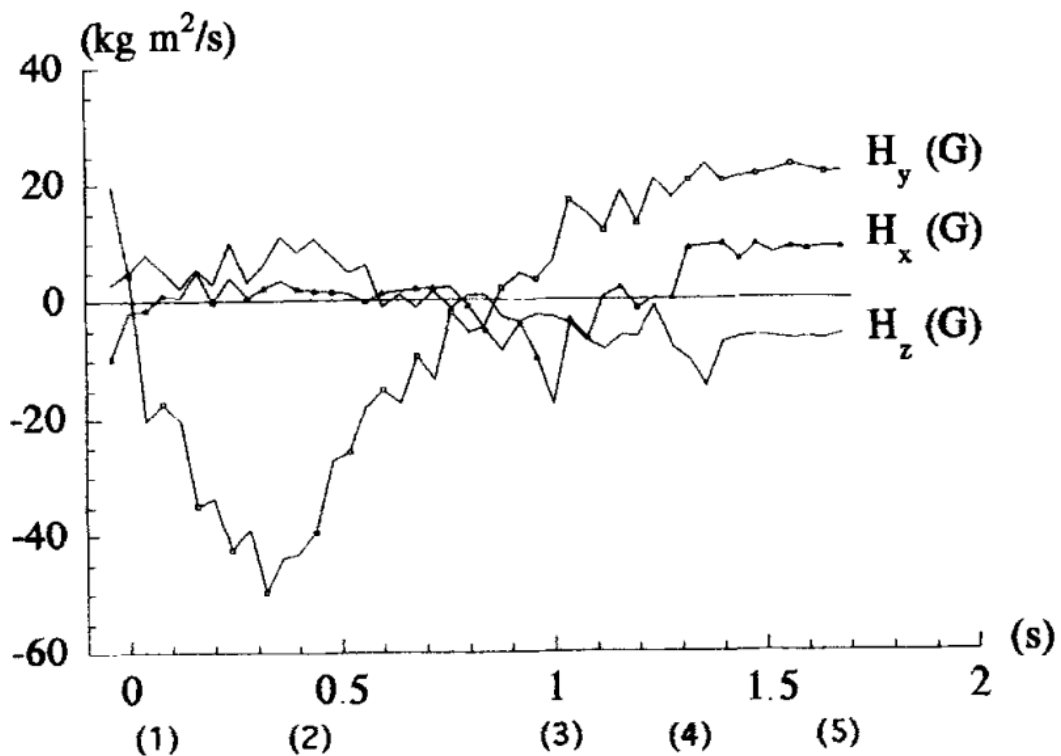


FIGURE 6. Angular momentum during pole vault. Indicators from the horizontal time axis has take-off (1), rock-back (2), pull-up (3), turn (4) and pole release (5). x = horizontal axis (direction of the runway), z = vertical axis and y = transversal axis. (Morlier & Cid 1996.)

In addition to the swing up motion, vaulter has slight positive angular momentum around transversal axis both before and after the swing-up motion. First positive angular momentum can be viewed as way to prepare for the energy exchanges to strain energy either creating larger bending moment to the pole during the take-off contact (Morlier & Cid 1996) or sacrificing some angular momentum to strain energy by delaying the swing up and increasing the compressive force before the swinging starts (Angulo-Kinzler et al. 1994). The second positive angular momentum and direction change occurs just before the free flight phase, when vaulter must use some energy or muscle work to create positive angular momentum to rotate itself around the crossbar (Angulo-Kinzler et al. 1994).

In the figure 6 at 1.4 seconds, there is slight increase in angular momentum both in vertical and horizontal axis. This is the point when vaulter creates slight angular momentum to turn the body in a direction which crossing the bar happens the ventral side first (Angulo-Kinzler et al. 1994; Morlier & Cid 1996).

3.4 Potential energy

In pole vaulting, potential energy is determined by the height of the vaulter's centre of gravity. Figure 7 shows the ranges of which the potential energy at the end of the jump is determined. At least in theory, vaulter could go over the crossbar above vaulter's centre of gravity if body position and momentum are optimal.

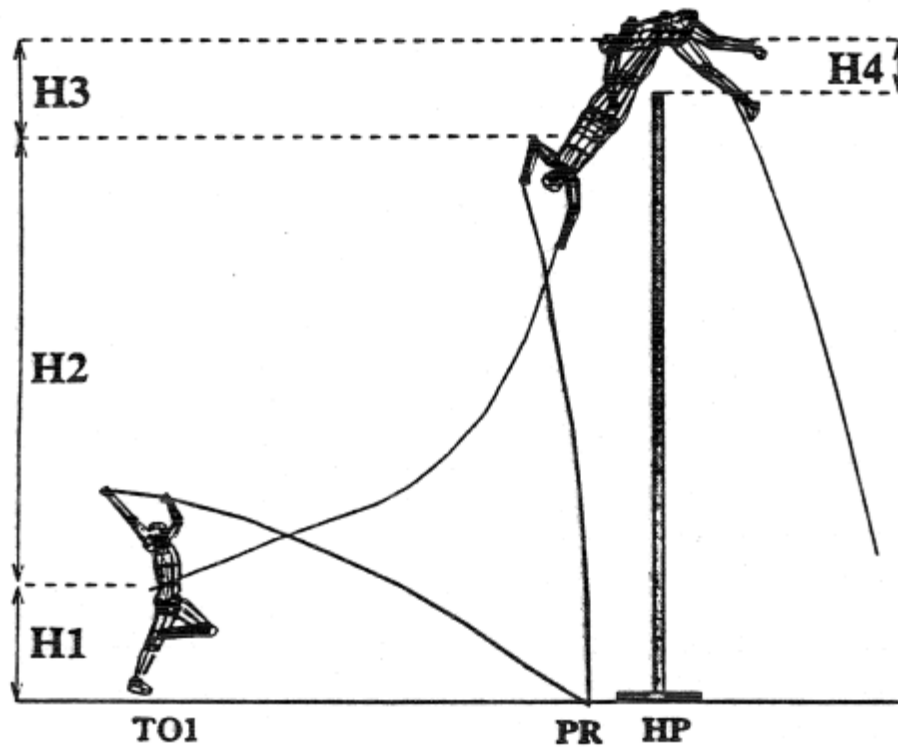


FIGURE 7. Height ranges from the vault. H1 = centre of gravity at take-off, H2 = difference between centre of gravity at take-off and pole release (i.e. height gained in the pole support phase), H3 = difference between height of the centre of gravity at pole release and its maximum (i.e. height gained in the free flight phase) and H4 = difference between maximum of centre of gravity and height of the crossbar. (Image from Angulo-Kinzler et al. 1994)

At take-off, take-off angle and the reaction force of the pole plant raises the centre of gravity a bit resulting a higher initial potential energy compared to potential energy at run-up (Angulo-Kinzler et al. 1994). Potential energy increases not linearly but smoothly after the take-off in the pole support phase (Frère et al. 2010). In the free flight phase, reducing vertical kinetic energy due to gravitation results to an increase in potential energy and reaches the maximum in a parabolic flight path (Angulo-Kinzler et al. 1994).

4 DIFFERENCES IN MEN'S AND WOMEN'S POLE VAULT

Difference in performance between men and women can mostly be explained by slower approach velocity (Grabner 1997; Cassirame et al. 2017). However, that does not explain all the differences, since men's approach velocity correlates more to the height than with women (Cassirame et al. 2017). Jump height prediction graph in relation to approach velocity was 61 cm lower for women than men between 1997-2003 but compared to earlier years in 1995-1997 gap was narrowed down by 35 cm (McGinnis 1997; McGinnis 2004). This is an indication of mechanical inefficiency compared to men, but a great leap forward in a short period.

In addition to differences in velocities, comparing 1995 world record holders in men and women were noticed that the pole bending phase lasts about same amount of time for both, but the pole straightening phase takes longer for female vaulter. Although male vaulters straightening phase was shorter, it was followed by the free-flight phase which was not observed in the female vaulter. The total time from maximum bend position to maximum height of the centre of gravity was longer for male vaulter. (Grabner 1997.)

Men's regression model for predicting performance emphasizes velocity more than women (74.4 % vs. 58,4%). Other factors were below 5 % for men, but for women amount of pole bend in relation to velocity explained 36,9 % of the performance. (Cassirame et al. 2017.) This is consistent with the findings from the Sydney Olympic games from 2000 where it was noticed that with greater angular momentum women bend their poles by sacrificing some of the mechanical energy of the body to strain energy of the pole. Whereas men add additional energy to the pole by bending the pole with muscle work rather than sacrificing mechanical energy. (Schade et al. 2004.) That might be one key feature why men jump higher with same amount of velocity.

Data collected from the world indoor championships in 2018 shows that in addition to slower approach velocity women had less steps in their run-up than men to generate that velocity. Also, they had higher take-off angle and lesser kinetic energy loss from the take-off which are

determinants of low grip heights and less stiff poles compared to men. (Hanley et al. 2019a; Hanley et al. 2019b.) Same could be noticed from earlier summer world championships in 2017. In addition to that, time of the pole support phase correlates negatively to the push off height for men, but not at all in women. (Gravestock et al. 2017a; Gravestock et al. 2017b.)

The data and coach's commentary section indicate that runway velocity affects less to performance than before for the elite vaulters of both sexes and differences are made in take-off velocity and phases after that (Gravestock et al. 2017a; Gravestock et al. 2017b.). Figure 8 combines runway velocity and height regression lines from athletes before 2004 and velocity-height data from the world championships in 2017 and world indoor championships in 2018. It indicates that women have narrowed down the gap between performance deficit in relation to runway velocity, and the limiting factor appears to be the velocity. Men's heights are almost all above the previous regression line which could mean some progress but are mostly affected by the level which data is collected before 2004. This is only applicable to elite level athletes because the newer data are from world championships, but clearly show the progress of women's performance.

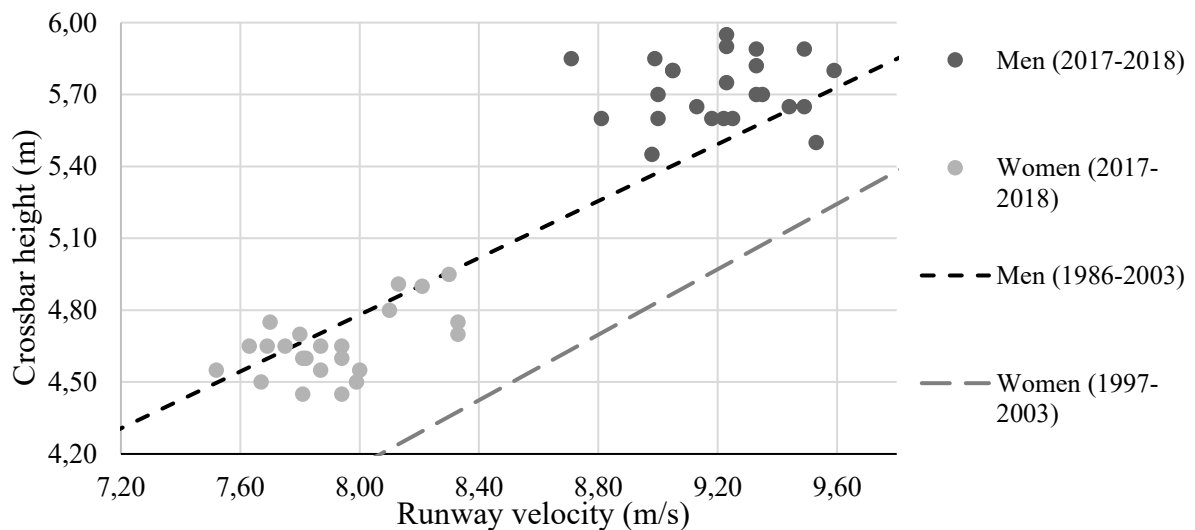


FIGURE 8 Approach velocities and crossbar heights from 2017 world championships and 2018 world indoor championships in comparison to regression lines from men between 1986-2003 and women between 1997-2003. Velocity-height data is form from Gravestock et al. (2017a; 2017b) and Hanley et al. (2019a; 2019b), and regression lines from McGinnis (2004).

5 PREVIOUS STUDIES OF POLE VAULT MECHANICS

Most of the previous studies have used kinematic analysis alone or in combination with other measurements like forces and velocities. They provide good opportunities for estimating both energy parameters and forces during the jump which is often too complex to be evaluated only with straight measurements. In addition, some optimization studies have been made when trying to find optimal values for best performance or pole properties. Recently, a few studies have been made on characteristics of the run-up phase. The following sections presents previous studies on energy parameters, vaulter-pole-interaction, optimization of performance and pole properties, and run-up characteristics. Finally, the last section discusses some limitations which were present in previous studies.

5.1 Mechanical energy

Mechanical energy of the vaulter has been studied lately with kinematic analyses (Arampatzis et al. 1997; Schade et al. 2000; Schade et al. 2004; Linthorne & Weetman et al. 2012). Mechanical energy can be calculated from 2 or 3-dimensional motion data and vaulter can be represented as a point mass for the centre of gravity energy or multi segmented object for total body energy. Schade et al. (2000) compared the differences between the calculation methods. Differences using the same vaulter model were small for 2 and 3-dimensional data. Between vaulter models, differences were larger even when using the same dimensional data. Despite differences in values, using 2-dimensional analysis and centre of gravity energy gives enough accuracy and reliability for many applications, but for more in-depth analysis 3-dimensional and whole-body models are preferrable. (Schade et al. 2000.)

Arampatzis et al. (1997) explored the mechanical energy behaviour from the 1997 world championships in Athens using centre of gravity energy. They found out that jump height correlated most with the total mechanical energy in the highest position of the centre of gravity. The initial energy during the take-off correlated well with the total energy at the end of the jump, but only provided good opportunities to a successful jump and needs effective technique to carry on the initial conditions to good performance (Arampatzis et al 1997). The

same correlation was confirmed by Schade et al. (2004) from 2000 Sydney Olympics. They calculated mechanical energy as a total body energy, which also considers the rotational kinetic energy of the vaulter. They found out that women had more angular momentum at swing which indicates a separate way to handle mechanical energy transformations during the jump compared to men. They also mentioned that in addition to motion analysis, some information about strain energy of the pole needs to be known to evaluate vaulter's actions on the pole in more detail. (Schade et al. 2004.)

Linthorne & Weetman (2012) examined how run-up velocity affects performance, kinematics, and energy transformations of the jump from an individual athlete. They used two-dimensional motion analysis and the segmented body model. Vaulter performed jumps from varied number of steps to change the run-up velocity. They noticed that jump height increased linearly with increasing run-up velocity calculated from the last step before take-off. They concluded that by increasing the run-up velocity, energy efficiency of the take-off and pole support phase is reduced. With shorter approaches, jump height increased mainly due to higher grip height, but with faster velocities the push height is mainly responsible to increased height. (Linthorne & Weetman 2012.)

5.2 Human-pole interaction

The significance of human-pole interaction has been observed but not quantified in most studies, due to lack of knowing forces needed to calculate the strain energy of the pole. Most of the studies made to explore human-pole interaction have been measured with combination of force plates and motion analysis. Figure 9 shows the setup for measuring forces under the take-off foot and the planting box. Forces measured under the planting box is needed to calculate actions on the pole support phase, but to investigate the plant, forces under the take-off contact is needed (Morlier & Mesnard 2007).

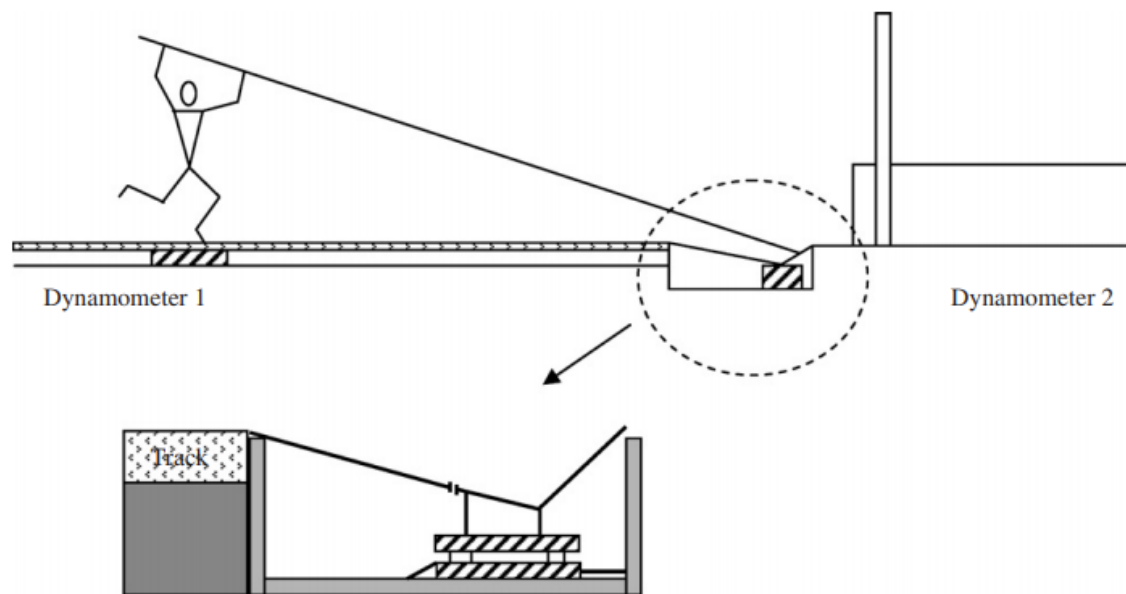


FIGURE 9. Dynamometer setup for evaluating vaulter-pole interaction from the plant onwards (Morlier & Mesnard 2007).

Arampatzis et al. (2004) explored the interaction between vaulter and pole utilizing motion analysis and force plates below take-off foot and planting box. They calculated the strain energy of the pole using formulas presented in chapter 3. Net energy increased from take-off to maximum of the pole bend, and from maximum bend to pole straightening even in both phases some energy loss occurred. (Arampatzis et al. 2004.) Schade et al. (2006) tested the reproducibility of the previously mentioned parameters and setup. They discovered that the parameters were reproducible and applicable to comparing interindividual performance differences or intraindividual variance during a training session or progression during the season (Schade et al. 2006).

Morlier & Mesnard (2007) used similar setup to explain the connection between moment exerted by the vaulter and performance. Total moment at a given time was calculated as a sum of impulse from take-off and moment exerted by the vaulter through hands. They managed to detect differences in moment produced between athletes and effect on performance but failed to recognise influence of different pole properties like stiffness. (Morlier & Mesnard 2007.) Schade & Arampatzis (2012) figured out how plant timing affects energy parameters after the

plant using force plates from the planting box combined to motion analysis. They hypothesised that earlier plant during take-off would result a higher energy level after take-off. However, they detected that plant timing did not change the amount of energy. Earlier plant led to earlier energy transfer to pole as strain energy which may affect the energy transformation patterns. They hypothesised that earlier plant leads lead to less mechanical energy and more strain energy also in the later phases of the jump which was not further investigated. (Schade & Arampatzis 2012.)

Frère et al. (2012) measured muscle activities from upper body muscles using electromyography to evaluate actions exerted to the pole. Energy transformations were calculated using two-dimensional motion analysis and activities were measured from m. deltoideus pars clavicularis, m. latissimus dorsi, m. triceps brachii, m. biceps brachii and m. infraspinatus. M. latissimus dorsi from both sides were responsible for the energy gain especially during maximal bend position, and other muscles were mainly working as a stabilising and coordinating muscles, not actively adding energy. (Frère et al. 2012.)

5.3 Simulations and modelling

Ekevad & Lundberg (1995) simulated energy gains when vaulter does active muscle work during the pole support phase. They used one elite vaulter as a reference model how vaulter works during the jump. They calculated body positions, direction of force vectors and other parameters from the reference and used that to simulate the effect of different pole properties. They approved models when pole reached vertical position and vaulter had enough energy to clear the bar. Even though many models were accepted, they could not be implemented in practice. For example, they noticed that using too low grip and stiff pole, vaulter did not have the strength nor time to perform the jump. Also, too high grip and less stiff pole did not work, because the pole would not have enough stiffness to return the energy against vaulter's body mass. For the optimal model, they calculated 1.27 times more energy at the end of the jump compared to the initial energy at take-off. (Ekevad & Lundberg 1995.) They carried out a similar study but using passive vaulter and a point mass for their models. They noticed that pole needed to be longer compared to their previous study, and with optimal pole properties,

energy coefficient was 0.87 which highlights the importance of the active muscle work during the jump. (Ekevad & Lundberg 1997.)

Linthorne (2000) simulated the jump using passive point mass model but focused on take-off angle in addition to pole properties. He used some restrictions that make jumping safer like restricting the amount of pole bend and making sure that small adjustments do not lead to dramatic differences to the jump. The simulations showed that impact from the plant is smaller when using elastic poles and vaulter could also lower the take-off angle which together led to a more efficient take-off. As a result, vaulter achieved higher grip height when using elastic poles. However, the optimal grip height was lower than maximal reachable grip, because a too high grip started to reduce achievable push height. (Linthorne 2000.)

Liu et al. (2011) continued with similar modelling to find optimal parameters for the pole vault while maintaining adequate horizontal velocity at bar clearance. They used vaulters with different physical characteristics in their model and noticed that in addition to height of the vaulter, weight plays a significant role in performance especially with high take-off velocities. They also found optimal values for each set of height and weight but highlighted the individuality of athletes and techniques. More importantly, they found out that optimal performance should be approached from the longer and less stiff pole and larger take-off angle. (Liu et al. 2011.)

Fukushima et al. (2014) used active bending moment producing robot to investigate the effects of the active vaulter. The robot produced a bending moment in the pole bending phase (positive bending) and assisted the pole straightening (negative bending) in the pole straightening phase. Active work increased the energy 14 %. By changing the bending direction after the maximum bending position resulted a higher jump than earlier switch. (Fukushima et al. 2017.)

5.4 Performance related factors from direct measurements

Cassirame et al. (2017) did a regression model of performance predicting factors that was collected with cameras, radar, and optical step analysis system. The most important performance predicting factor for both men (74.4 %) and women (58.4 %) was horizontal velocity, but for women the amount of pole bend in relation to velocity was the second most important factor (36.9%). (Cassirame et al. 2017.)

Frère et al (2017) investigated how a pole carry affects maximal running using radar behind the athlete. Using velocity-time-data they calculated estimates of the ground reaction forces and power output. They noticed a pole carry to cause power deficit that was caused by the deficit of both force and velocity production. (Frère et al. 2017.)

Needham et al. (2018) placed multiple cameras along the runway to detect how athletes regulate their running in the run-up phase. They detected individual patterns of run-up regulation and athletes that did not regulate their running. Regulation occurred mainly in the last couple of steps to achieve better take-off distance. It was noted that athletes with better abilities to regulate their running had better consistency in their jumps. (Needham et al 2018.)

Cassirame et al. (2019) investigated how successful and unsuccessful jump differ from varying levels of athletes. They found a small increase in take-off velocity when an athlete was able to do a successful jump. Also for women, horizontal distance from top hand to take-off foot was little higher in a successful jump than unsuccessful one which indicates the meaning of better body position at take-off. (Cassirame et al. 2019)

5.5 Limitations of previous studies

We have a good understanding how mechanical energy and strain energy of the pole behaves and how actions affect the athlete-pole interaction. Some optimisation studies of jump properties have been made like Ekevad & Lundberg (1995; 1997) and Liu et al. (2011), but they are limited on simulations. The state-of-the-art real-world studies combine motion data

and force measurements to create a good overview of the jump. Main limitation is the time needed to collect the data. Motion data has usually been manually digitised from videos and time to label all body parts take time. Other option is to use motion capture systems, but usually they need markers on the athlete that takes time to put on and might affect the performance. They are also not applicable to competition environments and are often expensive. Measuring forces usually needs force plates under the take-off foot and planting box which both need to be built in so that limits their use.

The inconvenience of doing research in pole vault limits the amount of data collected to the studies. Most studies collect their data from an individual competition or training session, which limits their applicability in addition to the amount of the data. So, that pole vault can be studied in a more volume and detail, we need more convenient ways to collect the data.

6 PURPOSE OF THE STUDY

The main purpose of this study was to determine which common factors in elite athletes predict performance in a competition. More precisely which factors beyond speed were important at run-up and take-off phases and how these factors and their relevance changed depending on gender. Research questions are the following:

1. Which common factors from run-up and take-off can be determined that influence athlete's performance in a competition?

Since this study focuses only on phases before the end of the take-off, total energy at peak centre of gravity cannot be used. Therefore, the focus lies on the initial energy at take-off which correlates well with the total energy at peak centre of gravity. (Arampatzis et al. 1997.) The hypothesis to the first question is that maintaining maximal mechanical energy at take-off results a better performance. Parameters to highlight are minimal horizontal velocity loss and centre of gravity vertical positional change in the take-off.

2. How factors from run-up and take-off that influence athlete's performance in a competition differ when considered both men and women separately?

The hypothesis to the second question is that women's performance might orient to higher grip height and relatively lesser stiff poles due to the lack of free flight phase (Grabner 1997). This was still present in 2017 world championships when women had lower push heights compared to men (Gravestock et al. 2017a; Gravestock et al. 2017b). So, the parameters that indicate high grip and less stiff pole are lower pole angle and minimal horizontal velocity loss at take-off. Men's performance is greatly affected by muscle work during the pole support phase (Schade et al. 2004), so determining possible factors are more challenging to identify from run-up and take-off. One possible distinguishing factor might be the ability to maintain horizontal velocity in the run-up and a greater horizontal velocity loss at take-off that indicates the use of stiffer poles (Linthorne 2000).

7 METHODS

Since the amount of processing power has increased and machine learning such as neural networks have become more widespread, modern technology could be used to gain more knowledge on analysing athletics performance. Choice of the methods was based on an idea that would solve the limitations from previous studies. The main requirements for the methods were: 1. Relatively quick to implement, 2. Possibility to scale to a larger data set and 3. Applicable to other phases of the jump.

7.1 Data

Data were collected as part of the Birmingham 2018 IAAF World Indoor Championships Biomechanics Research Project and was kindly provided by Dr. Athanassios Bissas who took part for the original research project and gave insights to help in this study. The athletes provided their written informed consent to participate in the project.

Original data set included videos from the competition recorded from five different locations in the pole vault finals, and from each male (n=15) and female (n=11) participant execution of the highest clearance was selected. Two of the camera views were used for 20 athletes, and one camera view for 6 athletes due to 5 missing videos and 1 invalid (appendix 1). Videos were captured by two Sony PXW-FS5 cameras operating at 1080p/200Hz. Measurement setup and the locations of the two cameras used are shown in the figure 10. Calibration of the area occurred before the competitions with calibration cube at two different locations along the runway, as seen in figure 11. The cameras had slight movement in between calibration frame shots and shots from the competition, so the camera views were aligned before the calibration.

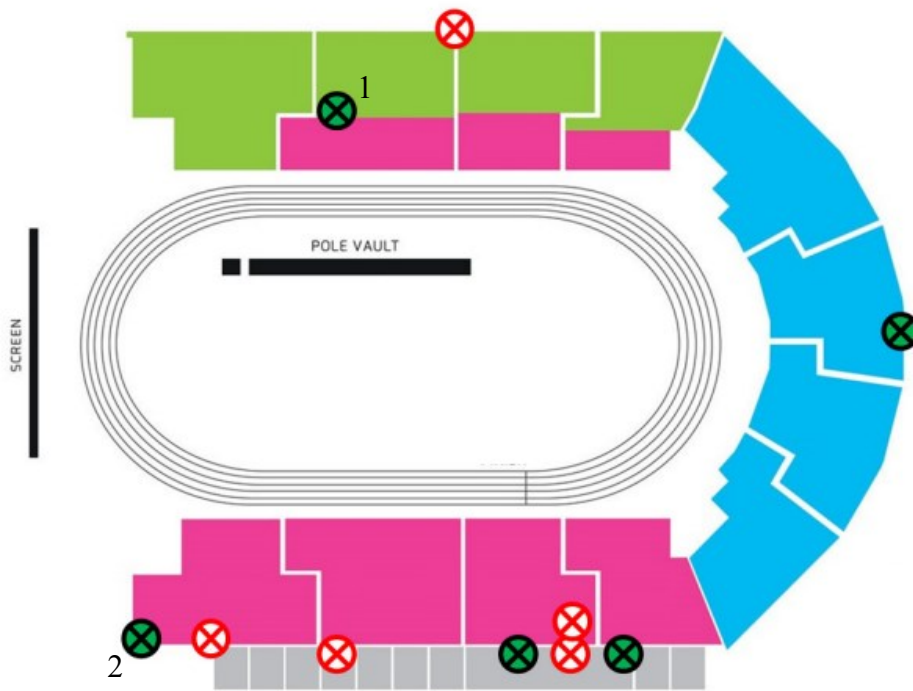


FIGURE 10. Camera placements for the men’s and women’s pole vault competition (black-green markers). Cameras that were used marked as 1 and 2. Figure modified from Hanley et al. (2019a).

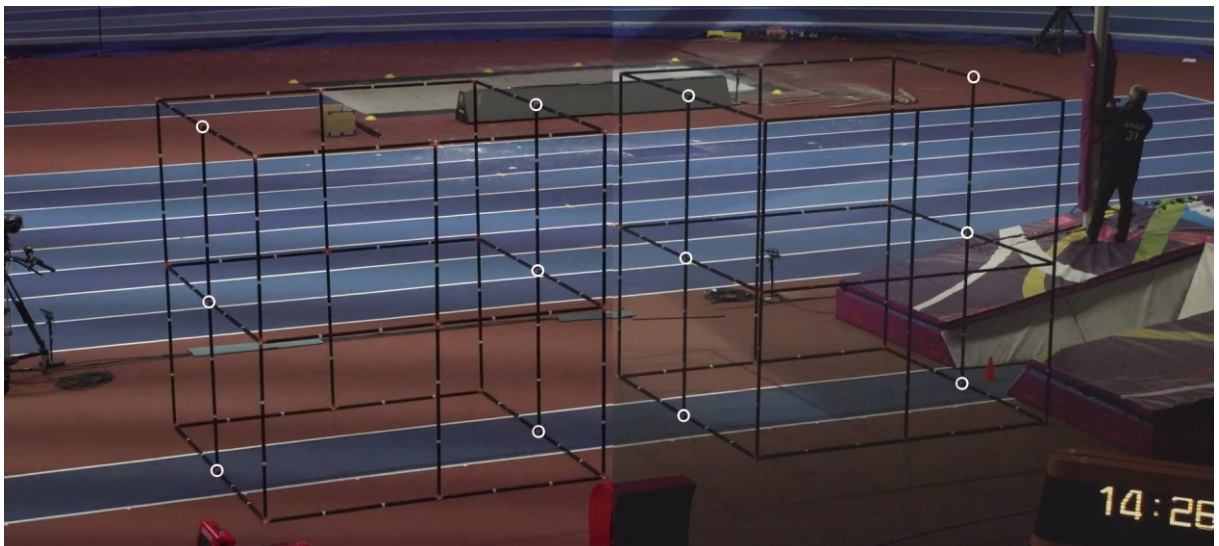


FIGURE 11. Calibration cube at two different locations edited into one image that is used to calibrate the area. Points used are surrounded by white circles.

7.2 Markerless motion capture

Motion data used in this study was created using neural network-based markerless method called DeepLabCut. DeepLabCut was chosen because it uses a concept called transfer learning which reduces the amount of data and processing power needed to train the network to a certain task. (Mathis et al. 2018.) Also, Cronin et al. (2019) applied it successfully to recognizing body parts from underwater running using minimal training data. To understand operating principles behind the recognition, the following section describes the fundamentals of neural networks and some key architectural designs of DeepLabCut proceeding to the details how DeepLabCut is used in this study.

7.2.1 Operating principle

An artificial neural network is a machine learning technique that's design was inspired by the learning mechanism of a human nervous system. A single unit of a neural network is called perceptron which basic architecture is introduced graphically in Figure 12 and the simplified mathematic formula is $y = \text{sign}\{\sum_{i=1}^n w_i x_i\}$. In the perceptron there is one output node that takes values of feature variables $[x_1, \dots, x_s]$ as input and for each variable there is a corresponding weight coefficient $[w_1, \dots, w_s]$. The sum of the products goes to the activation function (in this case sign function) that classifies the real value of the sum to either -1 or 1 which is then the prediction of the class from the inputs. (Aggarwal 2018, p. 5–6.)

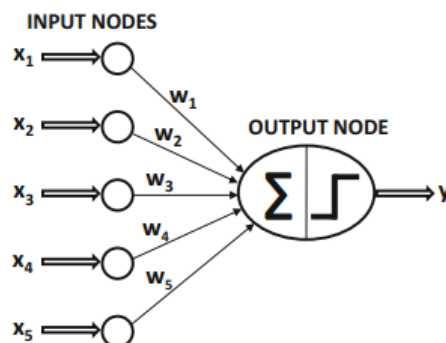


FIGURE 12. The basic architecture of the perceptron. Figure from Aggarwal (2018, p. 5).

In the multilayer neural networks, nodes (perceptrons) are layered and linked to each node on the next layer to solve more complex problems. Figure 13 shows the simplified structure of the neural network. The operating principle remains similar as with single perceptron, but now the calculations are done in each node which outputs are guided to the nodes on the next layer. (Aggarwal 2018, p. 17-20). For the method used in this study, the most important thing to understand is that the neural network takes values that define the output as input and does calculations on its nodes to differentiate the input sets to predict the expected output.

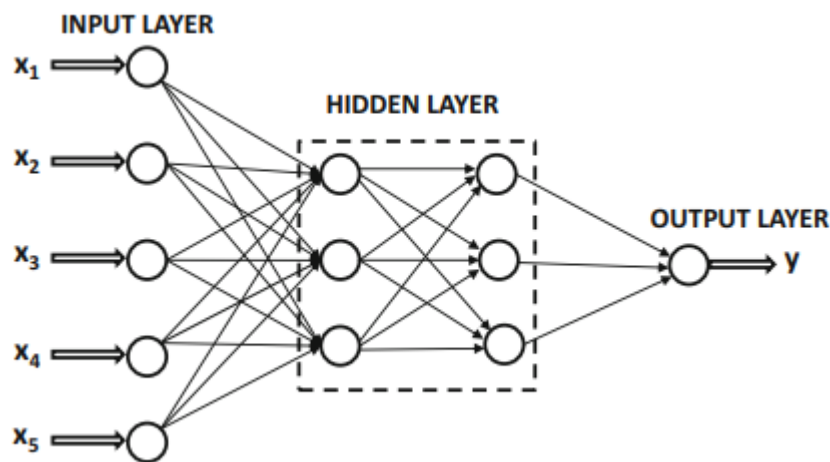


FIGURE 13. The basic architecture of multilayer neural network with two hidden layers and one output layer. Figure from Aggarwal (2018, p. 18).

To make the neural network work as intended, it must be trained with known input-output pairs called training data. The objective of the training is to minimize the difference between networks output and the expected output (i.e. training error). Training is done iteratively by feeding input value sets one by one in a random order to the network. Then the weights are adjusted in a direction which reduces the training error from the given and expected outputs, and this procedure will be repeated until the accuracy no longer improve. (Aggarwal 2018, p.7.) The goal of the training is to create a neural network that can generalize its decisions outside the training data to previously unseen inputs. This can be evaluated by feeding the network with unseen testing data with known outputs and comparing the output from the network with known output (i.e. test error). Poor generalization can be due to a small amount

of training data in which case the network cannot learn the expected task. Other common cause is that the network creates a too complex model taking into account every little detail from the training data impairing its generalizability (i.e. overfitting). (Aggarwal 2018, p.25-26.)

DeepLabCut uses variation of the deep residual neural network (ResNet) introduced by He et al. (2016). ResNet in DeepLabCut is a convolutional network that has been tested on the ImageNet object recognition benchmark and pre-trained to locate body parts from an image. (Mathis et al. 2018.) Convolutional networks are built on components called convolution layers which perform convolution operations to extract features from images and other grid like structured data. Simplified working example of the convolution operation is introduced in Figure 14. Convolution operation runs a feature detecting weight grid across all the possible locations in the input grid to create a new output grid which is composed of dot product between the weight grid and input grid at each location. Output grid represents where matching patterns (features) from the input are located. (Aggarwal 2018, p.315-320.; Yamashita et al. 2018.)

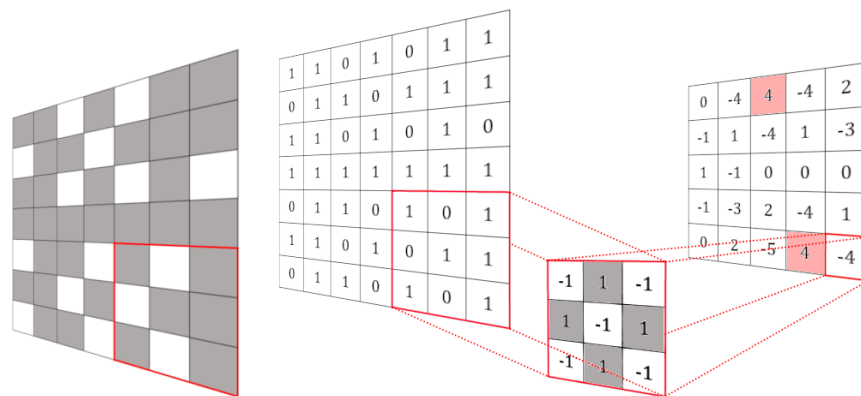


FIGURE 14. Example of convolution operation which finds most probable locations of the desired figure. Starting from the left, matrices are the visual data, the data in a numerical form, numerical filter (combined with visualisation of the figure to look for) and the output matrix. Larger value in the output matrix represents the higher probability of the desired matrix location.

ResNet differs from a traditional convolutional neural network with its use of deep residual learning and shortcut connection. Residual learning is a learning concept where instead of fitting function $H(x) = y$ in the network layer, function is changed to the form $H(x) = F(x) + x = y$. Then in the learning phase only $F(x)$ is learned, and x is mapped back to the output y (see Figure 15). This allows evaluation of the $F(x)$ in a way that if the learned function $F(x)$ does not add any accuracy compared to just input x , $F(x)$ can be skipped with shortcut connection and the original x will determine the output. (He et al. 2016.) This allows the ResNet to adapt per feature how many convolutional layers are needed to recognize each feature and thus reducing the total number of operations because simpler features do not need as many layers as more complex features (Aggarwal 2018, p.347-349).

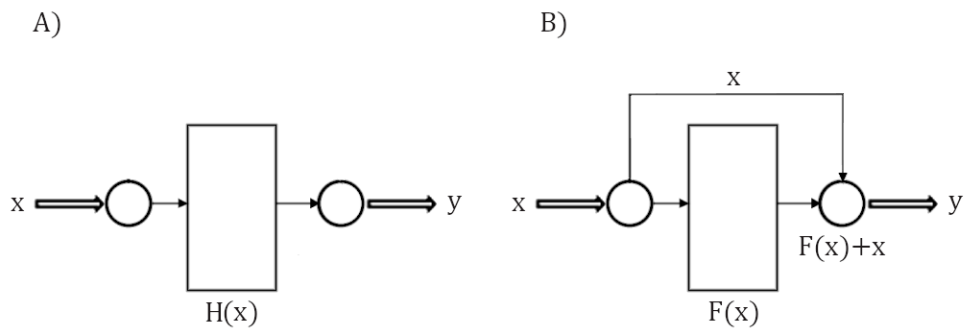


FIGURE 15. A. Traditional neural network layer. B. Residual neural network layer.

In DeepLabCut, pre-trained ResNet is used to specialize to a new task by training it with new application specific training data. Training data consist of images and corresponding locations of features in each image. (Mathis et al. 2018.) Output from the convolutional network can be combined with deconvolution which is basically opposite operation compared to a convolution. It is used to decode the information from the output to recreate representation of the features found from the input. (Aggarwal 2018, p.357-359.) In DeepLabCut, deconvolution layers up-sample the information back to the input resolution and provide spatial probability density map where different parts are most likely located (Mathis et al. 2018).

7.2.2 Training data

Videos were synchronized and cut to include 4 last foot-ground-contacts of the run-up and take-off completely. Resolution of the videos was down sampled to 540p to fasten the learning of the network, but the final motion data was upscaled back to the 1080p. Training data for the camera 1 consisted of 7 frames per athlete (22 athletes total, 4 videos were missing) and 6 frames per athlete for the camera 2 (25 athletes total, 1 video was missing) (appendix 1). For this application, all possible videos from all athletes were used in training and frames were automatically selected by DeepLabCut default parameters. Total frames per camera were 154 for the camera 1 and 150 for the camera 2, and the frames were then labelled with manually recognized body landmarks as seen in figure 16. Obtained frames were then split into 90/10 training and testing data sets. Training was done 200 000 iterations using ResNet-50 pre-trained network in the google colab platform. Cut-off value (i.e. probability) for acceptable recognition was chosen to be 0.8.

The aim was to recognize all landmarks chosen from each frame of each video analysed, but some irregularities had to be overcome. Cronin et al. (2019) reported problems with DeepLabCut such as other body part blocking the target body part or some incorrect placing which both were inherited to this project. Figure 16 shows how some landmarks (elbow and hip) are on the opposite side of the body and thus not recognized to the training data.



FIGURE 16. Example of the labeled training data.

7.2.3 Motion data processing and validation

Once training the network was done, pixel values from the DeepLabCut recognition was transformed into two-dimensional real-world-coordinates using direct linear transformation (DLT) -method (Abdel-Azis & Karara 1971). Mainly both cameras were used for DLT-transformation, but 6 athletes had only one camera view. In addition to that, the probability value of each body part recognition was used in a way that probability had to exceed the cut-off value 0.8. If value was not exceeded or view was missing, only another camera was used in that time point and body part. In the situation where all camera views were discarded, coordinate was set to zero (0,0) and filtering handled it later.

Two filters were used to smooth the data and more importantly deal with multiple consecutive missing coordinates. Firstly, missing coordinates were patched with interpolating values linearly between the outermost known values. After that, a second-order low pass Butterworth filter was used with cut-off frequency of 15 Hz to smooth the data.

Validating of the markerless method was done through train and test errors with unfiltered data. Additional validation was done by comparing values calculated from filtered motion data to the values from original reports (calculated from the manually digitised videos) done by Hanley et al. (2019a; 2019b). Variables used in the validation (Table 1) were same as Hanley et al. (2019a; 2019b) used in their analyses.

TABLE 1. Variables used to validate markerless method.

Variable	Description
Runway velocity (m/s)	The mean horizontal velocity during the mid-section of the runway (between 11-6 m for men and 10-5 for women).
3rd last contact distance (m)	The horizontal distance from the third last contact (foot tip marker) to the end of the planting box
Horizontal plant velocity (m/s)	The centre of gravity horizontal velocity at the time of pole plant.

Horizontal take-off velocity (m/s)	The centre of gravity horizontal velocity at the time of take-off.
Resultant take-off velocity (m/s)	The resultant centre of gravity horizontal velocity at the time of take-off.
Take-off angle (deg.)	The angle between the direction of the resultant take-off velocity and the horizontal plane at take-off.
Take-off distance (m)	The horizontal distance from the plant box to the foot tip of the take-off leg at take-off.
Step length ratio	The ratio of the last step length to the 2nd last step length.
CoG height at take-off (m)	The vertical distance between the runway and the centre of gravity at take-off.
Pole angle at take-off (deg.)	The angle between the pole and the ground at take-off.
Take-off position (m)	The horizontal distance between the foot tip of the take-off leg and the upper grip at the instant of take-off.
Grip width (m)	The distance between the upper and lower grips on the pole.

7.3 Variables

Landmarks used in motion capture were head, shoulders, elbows, wrists, middle of the fists, hips, knees, ankles, and foot tips and were selected that athlete's motion and technical choices were possible to calculate and identify. All body landmarks were not needed to directly define parameters but were still used to calculate the centre of gravity locations for different body parts and for the whole body using de Leva (1996) method. Moments of times for the touchdown and take-off for the last four contacts and plant were manually determined from the videos.

Because the connection between jump height and velocity is known (Linthorne & Weetman 2012), performance metric used instead of the height of the crossbar was the amount of potential energy needed to go over the crossbar (J/kg) divided by the mean total energy (J/kg)

during the mid-section of the runway (between 11-6 m for men and 10-5 for women) called energy conversion ratio. The proportional metric does not highlight velocity as a differentiating factor and allows other parameters to increase their relevance. Also, it allows comparison between men and women directly. Variables used in this study were inspired by the Birmingham report (Hanley et al. 2019a; Hanley et al. 2019b) and Cassirame et al. (2018) but modified to suit the proportional metrics and are presented in the Table 2.

TABLE 2. Variables used in the pole vault performance analyses.

Variable	Description
Step length (m/s)	Mean step length from 4 th last contact to take-off contact.
Step rate (steps/s)	Mean step rate from 4 th last contact to take-off contact.
Step length ratio	The ratio of the last step length to the 2nd last step length.
Plant timing (ratio)	Time from the take-off contact touchdown to the plant in relation to the take-off contact duration.
Take-off position (m)	The horizontal distance between the foot tip of the take-off leg and the upper grip at the instant of take-off.
Take-off angle (deg.)	The angle between the direction of the resultant take-off velocity and the horizontal plane at take-off.
Velocity change from run-up to plant (ratio)	The change in horizontal velocity between runway velocity and pole plant in relation to the horizontal runway velocity.
Velocity change from plant to take-off (ratio)	The change in horizontal velocity between pole plant and take-off in relation to the horizontal velocity at plant.
Ratio of centre of gravity and reach height	The ratio of the vertical distance between the runway and the centre of gravity and vertical distance between the runway and the top grip at take-off.
CoG vertical change from plant to take-off (m)	The change in vertical distance between centre of gravity and ground level from plant to take-off.
Pole bend (ratio)	The amount of pole bend (chord reduction) from plant to take-off.
Pole angle (deg.)	The angle between the pole and the ground at take-off.
Grip width (m)	The distance between top and bottom grip.

7.4 Statistical analysis

Statistical analysis was done with IBM SPSS Statistics software version 26.0.0. Apart from the evaluation of the error of motion recognition (root mean square error between manually recognized and the network recognized landmarks), which was provided by the DeepLabCut library. Values from Hanley et al. (2019a; 2019b) were compared to the corresponding values calculated using this method using paired samples T-test.

All variables used in analyses were not normally distributed by the Shapiro-Wilk's test of normality, so the Spearman's correlation was used to analyse correlations. Principal component analysis (PCA) was used to explore the underlying structure behind correlating variables. Kaiser-Meyer-Olkin test of sampling adequacy and Barlett's test of sphericity was taken into account before further analysis was done. Result from the PCA was also used in creating standardized value that represented the behaviour of related variables.

Differences in variable values between men and women were tested using independent samples T-test. Homogeneity of the variances was tested with Levene's test of variance to determine if equal variances should be assumed. A multiple linear regression was used for the selected groups to determine if the energy conversion could be predicted with selected variables. Standardised coefficients from the models were used to compare the effects between variables. Standardised coefficients are the relative coefficients obtained when variables are all transformed into standard scores that allow then the comparison between the relative strengths between coefficients.

8 RESULTS

8.1 Method performance

Camera 1 had error (RMSE) of 2.66 pixels for the training data and error of 3.36 pixels for the unseen testing data. Camera 2 had error of 2.3 pixels for the training data and error of 3.29 pixels for the testing data. Discarding likelihood values below 0.8 lowered the test error by 0.03 of a pixel for camera 1 and 0.26 of a pixel for camera 2. The difference of 3 pixels in the frame corresponds to a difference of about 3-4 cm in real-world-difference in both cameras. Figure 17 shows the typical differences in recognition.

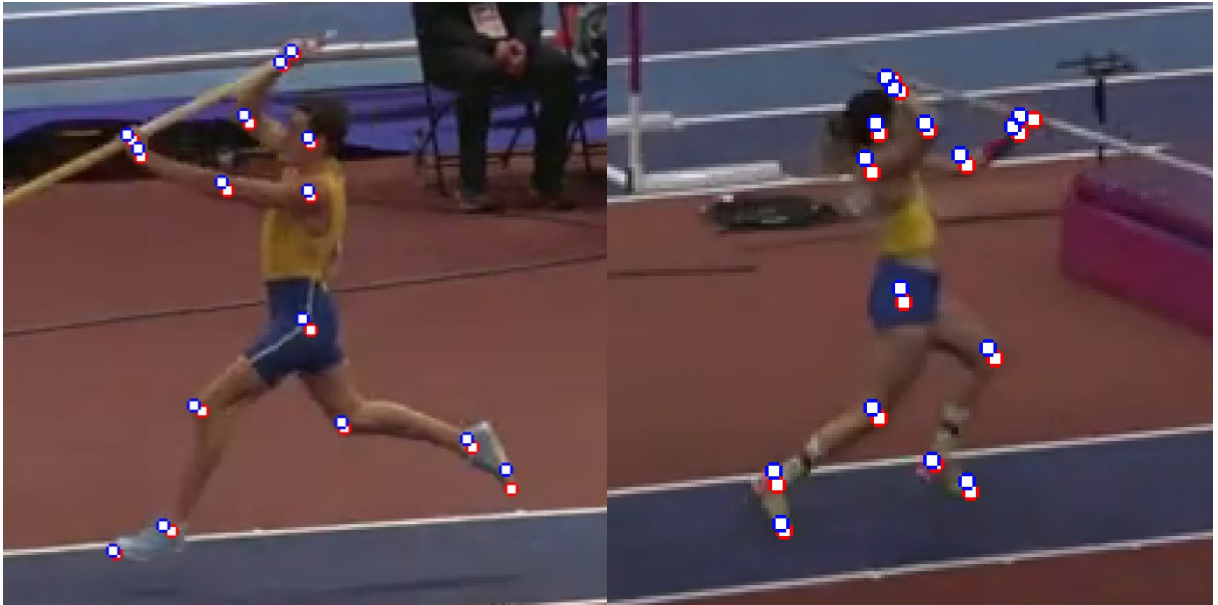


FIGURE 17. Manually recognized landmarks (markers circled in red) and DeepLabCut's recognized landmarks (markers circled in blue)

Figure 18 and 19 shows the variable-wise differences in percentages between obtained values using this method and reference values from the Hanley et al. (2019a; 2019b). The differences were mostly similar between men and women even though both groups had their own calibration which might have influenced the values.

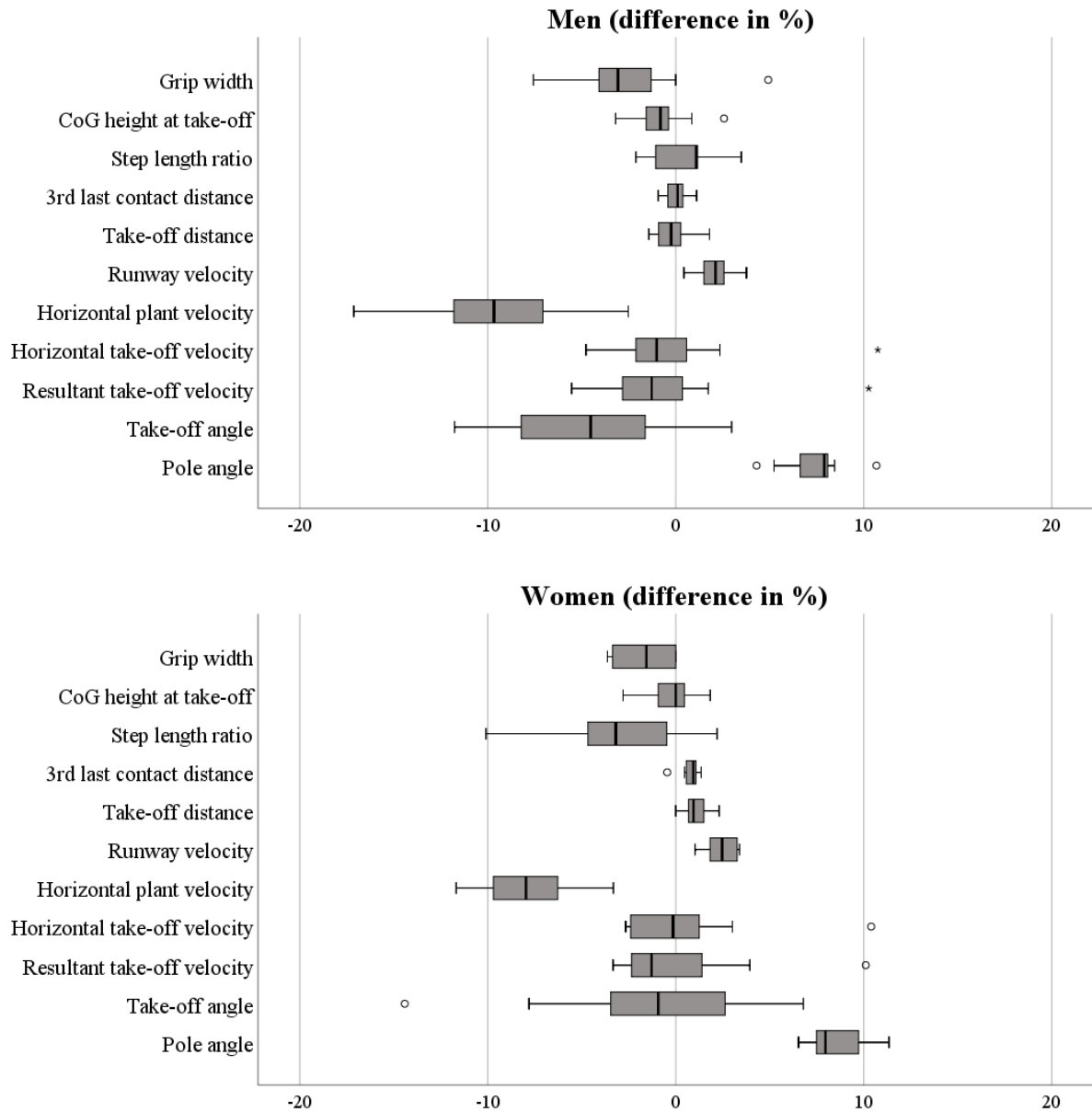


FIGURE 18. Differences in variable values as a percentage between values calculated from motion data by trained neural network and reference values from manually labelled data. Take-off position is in Figure 19 since it had way higher values compared to others.

Statistically significant differences in spatial values compared to the reference in men were on average lower values in grip width (-2 ± 2 cm, $t(14) = -3.69$, $p < 0.01$) and centre of gravity height at take-off (-1 ± 2 cm, $t(14) = -2.236$, $p < 0.01$). In women, significant differences were on average lower values in grip width (-1 ± 1 cm, $t(10) = -3.708$, $p < 0.01$) and step length ratio (-0.02 ± 0.03 , $t(10) = -2.798$, $p < 0.01$), and higher values in 3rd last contact distance to

planting box ($+7 \pm 5$ cm, $t(10) = 4.822$, $p < 0.01$) and take-off distance to planting box ($+4 \pm 3$ cm, $t(10) = 5.224$, $p < 0.01$). Take-off position did not show significant differences for both groups, even though it had large percentage outliers (Figure 19) due to small absolute values and small in value but larger in percentage differences. Generally the differences and variations were mostly small, so the method worked well for the spatial variables.

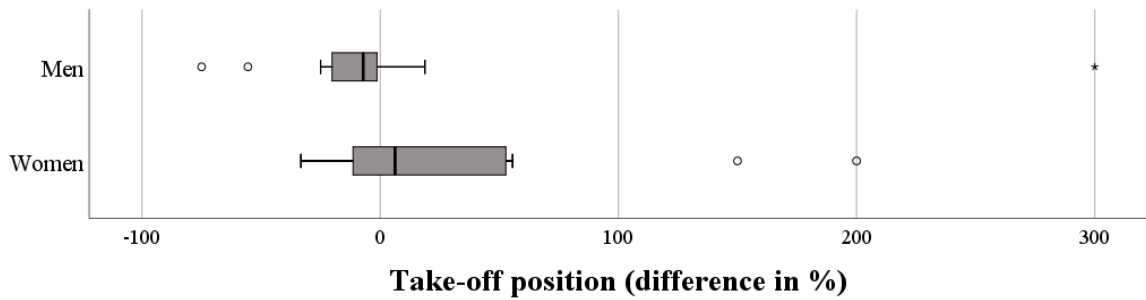


FIGURE 19. Differences in take-off position values as a percentage between values calculated from motion data by trained neural network and reference values from manually labelled data.

For velocities, statistically significant difference to the reference was larger values in runway velocity in men ($+0.18 \pm 0.08$ m/s, $t(14) = 8.353$, $p < 0.01$) and in women ($+0.19 \pm 0.07$ m/s, $t(10) = 9.093$, $p < 0.01$) but the difference was consistently higher. Horizontal plant velocity was way off in men (-0.90 ± 0.37 m/s, $t(14) = -9.304$, $p < 0.01$) and in women (-0.63 ± 0.21 m/s, $t(10) = -9.921$, $p < 0.01$). Runway and take-off velocities being in line or consistent with the reference showed that the method was usable for determining velocities, but some unexpected differences and variances were present in comparisons.

In men, observed take-off angle was on average slightly smaller (-0.80 ± 0.85 deg., $t(14) = -3.664$, $p < 0.01$). Observed pole angle was way higher in men ($+2.04 \pm 0.40$ deg., $t(14) = 19.856$, $p < 0.01$), which was also present in women ($+2.47 \pm 0.42$ deg., $t(10) = 19.437$, $p < 0.01$). The performance is adequate with angles. Reasons for the differences are hard to detect since take-off angle had values well aligned but varying more with the reference, and pole angle had smaller variations while being significantly different.

8.2 Relationships between variables

Run-up variables showed no significant correlation between each other (Table 3). Even though it was not statistically significant, there seemed to be a slight trend that athletes with shorter step lengths had higher step rates and vice versa. Correlation between step length ratio was possibly affected by the fact that last step was included to the calculations of step rate and length.

TABLE 3. Pairwise correlations between run-up variables.

	Step length ratio	Step rate
Step length	0,203	-0,321
Step rate	-0,243	

Strongest correlations between variables were found with take-off related variables apart from grip width, take-off angle and pole angle (Table 4). Plant timing, take-off position, velocity change from run-up to plant and from plant to take-off, vertical centre of gravity change from plant to take-off, ratio of the centre of gravity and reach height and pole bend from plant to take-off correlated all significantly between each other.

TABLE 4. Pairwise correlations between take-off variables. ** $p < 0.01$ and * $p < 0.05$ statistically significant correlation. Blue background indicates significant negative correlation and red positive correlation.

	Plant timing	TO position	TO angle	Vel change to plant	Vel change to TO	CoG vertical change	CoG to reach ratio	Pole bend	Pole angle	Grip width
Plant timing		-0,946**	-0,036	0,872**	-0,902**	0,803**	0,691**	0,937**	0,060	0,113
TO position	-0,946**		0,018	-0,830**	0,917**	-0,776**	-0,692**	-0,889**	0,074	-0,194
TO angle	-0,036	0,018		-0,123	-0,151	0,279	-0,012	0,061	0,212	-0,342
Vel change to plant	0,872**	-0,830**	-0,123		-0,814**	0,677**	0,622**	0,843**	0,205	0,078
Vel change to TO	-0,902**	0,917**	-0,151	-0,814**		-0,865**	-0,587**	-0,896**	-0,103	-0,066
CoG vertical change	0,803**	-0,776**	0,279	0,677**	-0,865**		0,586**	0,785**	0,037	0,151
CoG to reach ratio	0,691**	-0,692**	-0,012	0,622**	-0,587**	0,586**		0,661**	-0,413*	0,342
Pole bend	0,937**	-0,889**	0,061	0,843**	-0,896**	0,785**	0,661**		0,132	0,131
Pole angle	0,060	0,074	0,212	0,205	-0,103	0,037	-0,413*	0,132		-0,341
Grip width	0,113	-0,194	-0,342	0,078	-0,066	0,151	0,342	0,131	-0,341	

Previously mentioned seven take-off related variables were chosen to the closer inspection of underlying structure behind take-off variables and selection to the principal component analysis (PCA). Even though velocity decreases both before and after the plant correlate to the other variables, they were left out of the PCA because they might be also indicators of either run-up variables or usage of less stiff poles (Linthorne 2000). Also centre of gravity height to reach height ratio were left out of the PCA, since its correlation were lower to plant timing and take-off position compared to the centre of gravity vertical change. So plant timing, take-off position, pole bend before take-off and centre of gravity vertical change were chosen to the PCA to see if their behaviour can be explained with one component. As it turns out, new variable called take-off technique explains 89 % of the total variation between included variables, and all underlying variables correlate to the new standardized technique variable (Table 5).

Table 5. Results from the principal component analysis and key values from the newly formed variable.

Total variance explained by the principal component	
Eigenvalue	3,570
% of Variance	89,246
Variable-wise correlation to the principal component	
	r
Plant timing	0,978
Take-off position	-0,963
CoG vertical change from plant to take-off	0,899
Pole bend from plant to take-off	0,937
Standardised variable-wise coefficients to the new variable	
Plant timing	0,274
Take-off position	-0,270
CoG vertical change from plant to take-off	0,262
Pole bend from plant to take-off	0,252
Standardised new variable	
Mean	0.00
Standard deviation	1.00
Minimum	-1,88
Maximum	1,76
Variance	1.00

Examples of the take-off techniques and corresponding values are in Figure 20. Take-off technique has positive values when: 1. Plant timing is close to the take-off contact touchdown (i.e. early plant), 2. Top grip's horizontal position is behind the take-off foot tip, 3. Centre of gravity height raises from plant to take-off and 4. Pole bends before the take-off. Take-off technique has negative values when: 1. Plant timing is close to the take-off, 2. Top grip's horizontal position is on the front of the take-off foot's tip, 3. Centre of gravity height remains similar from plant to take-off and 4. Pole does not bend or bends slightly before take-off.



Figure 20. Three take-off techniques whose values are -1.88 (left), 0.14 (middle) and 1.25 (right).

Further modifications to the variables used in performance analysis were that reductions in velocities were combined and described as a total velocity change during take-off. Reason for this was that the newly formed take-off variable correlated highly with velocity reduction patterns and the whole amount of reduction might be one performance determining factor as hypothesised.

8.3 Performance determinants

Using multiple linear regression, cleared height of an athlete could be calculated ($R^2 = 0.996$) with runway velocity and energy conversion ratio (Figure 21). Standardised coefficients (runway velocity = 1,224 and energy conversion = 0,447) gave more weight to the runway velocity but were not able to predict the height as accurately by itself. Since the energy

conversion ratio describes the athlete’s ability to transfer his/her energy into a clearance of the bar, it was used as a metric to evaluate performance in the following analyses.

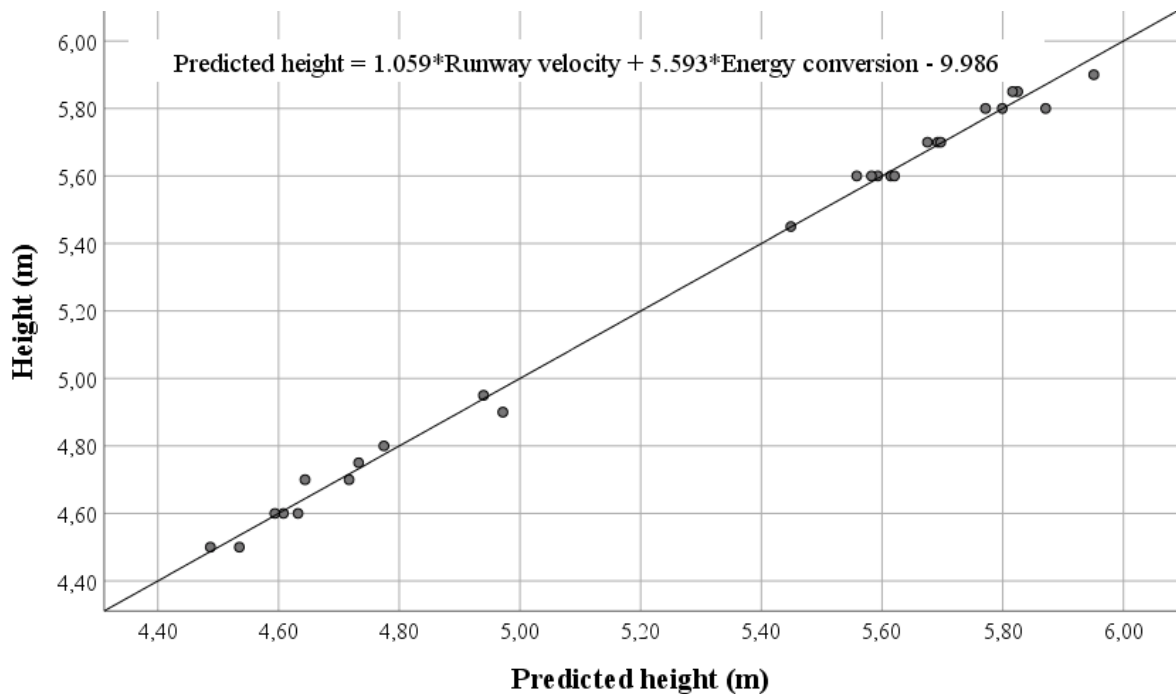


FIGURE 21. Comparison between height (m) and predicted height (m) using energy conversion and runway velocity.

Correlations to the energy conversion ratio were explored using previously selected variables (Table 6). Significant correlations were with step length ($r = -0,597$, $p < 0.01$), pole angle ($r = 0,612$, $p < 0.01$), and total velocity change during take-off ($r = 0,428$, $p < 0,05$). Based on these results, shorter step length, higher pole angle (probable determinant of lower grip height) and maintaining horizontal velocity would individually be beneficial to the energy conversion.

TABLE 6. Correlations to the energy conversion ratio. ** $p < 0.01$. * $p < 0.05$

	SL	SR	SLR	TO technique	TO angle	TO vel change	CoG ratio	Pole angle	Grip width
Energy conversion	-0,597**	-0,020	0,025	-0,075	0,013	0,428*	-0,348	0,612**	-0,258

Linear regression model for predicting the energy conversion was created ($R^2 = 0,639$) and the variables with corresponding coefficients and standardized coefficients are in the Table 7. Comparison of the energy conversion and predicted value are in Figure 22.

TABLE 7. Linear regression model coefficients for the energy conversion

Variable	Coefficient	Standardized Coefficient
Constant	1,954	
Step length	-0,091	-0,335
Step rate	-0,006	-0,026
Step length ratio	0,165	0,232
Take-off technique	0,028	0,662
Take-off angle	0,003	0,152
Take-off velocity change	1,053	0,728
CoG to reach ratio	-1,442	-0,386
Pole angle	0,011	0,073
Grip width	-0,004	-0,070

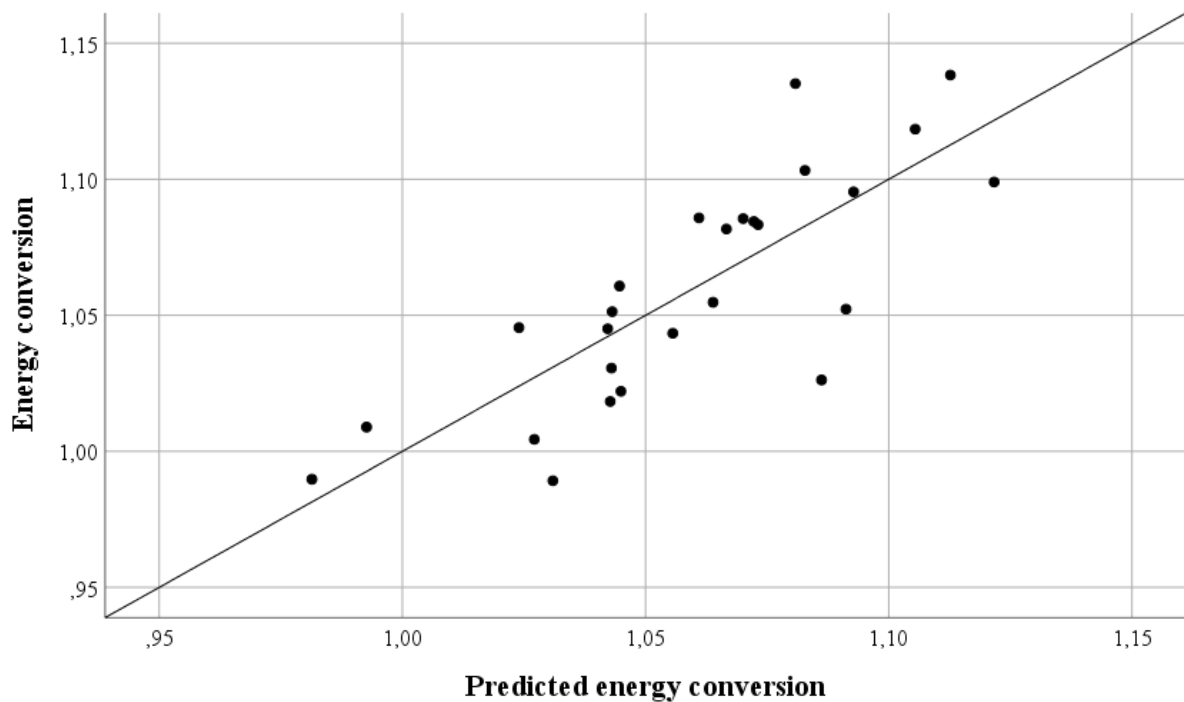


FIGURE 22. Relationship between multiple linear regression predicted energy conversion and energy conversion.

8.4 Differences in variables and performance between men and women

Based on mean values, take-off technique was similar between men and women, but women had on average slightly better energy conversion than men (Table 8). Figure 23 shows the negative correlation between runway velocity and energy conversion in both men ($r = -0,779$, $p < 0.01$) and women ($r = -0,864$, $p < 0.01$). Since the negative correlation between velocity and energy conversion, better energy conversion of women could be due to slower runway velocity. On the other hand, energy conversion behaved within the groups so that the slower athletes had better energy conversion and faster athletes worse regardless of the absolute runway velocity.

Table 8. Independent samples T-test between men and women. Statistically different ($p < 0.05$) values are highlighted. Negative values of the mean difference means that men had lower values and positive higher values.

Variable	Mean difference	t	df	p (2-tailed)
Energy conversion	-0,03	-2,235	24	0,035
Take-off technique	0,10	0,253	24	0,802

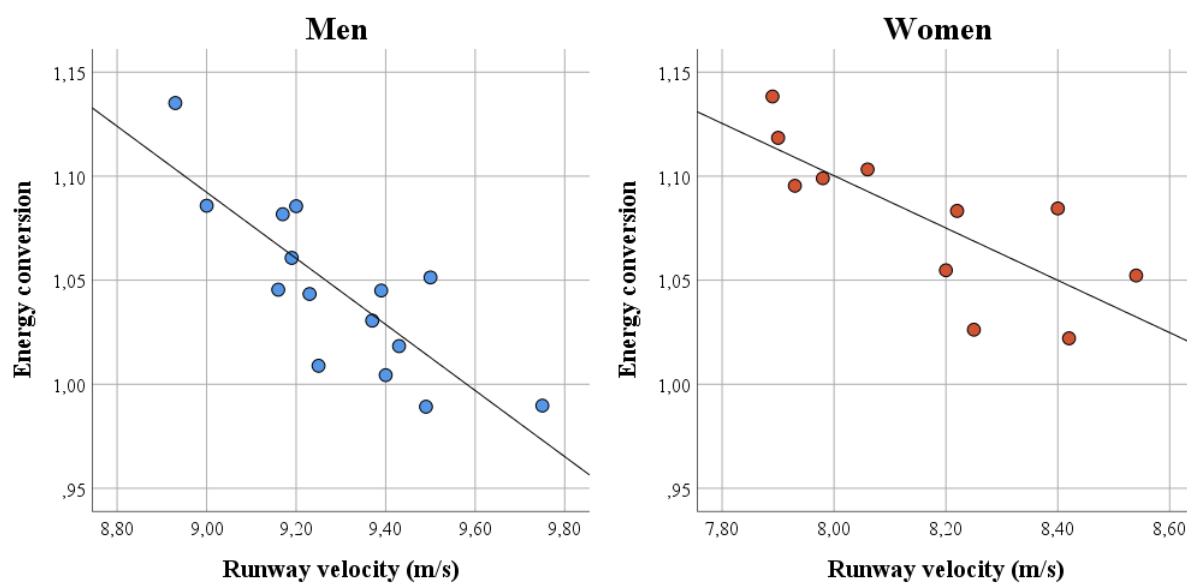


FIGURE 23. Relationship between energy conversion and runway velocity.

From the original set of variables which mean values differed significantly between men and women were step length, pole angle and grip width (Table 9). If needed, the values of the variables can be seen in appendix 2. Step length and pole angle were the two most determining factors to the general energy conversion model and may explain the weights in the model since the energy conversion differences between men and women.

Table 9. Independent samples T-test between men and women. Statistically different ($p < 0.05$) values are highlighted. Negative values of the mean difference means that men had lower values on average.

Variable	Mean difference	t	df	p (2-tailed)
Step length (m)	0.25	6.603	24	0.000
Step rate (steps/s)	0,02	0.300	14,988	0.768
Step length ratio	0,02	0.680	24	0.503
Plant timing (ratio)	-0,03	-0.309	24	0.760
Take-off position (m)	-0,06	-0.657	24	0.517
Take-off angle (deg.)	-0,77	-0.997	24	0.329
Velocity change from run-up to plant (ratio)	-0,15	-1.127	24	0.271
Velocity change from plant to take-off (ratio)	-0,12	-0.656	24	0.518
CoG vertical change from plant to take-off (m)	0,01	0.843	24	0.407
Ratio of centre of gravity and reach height	0,01	1.475	24	0.153
Pole bend from plant to take-off (ratio)	0,00	-0.177	24	0.861
Pole angle at take-off (deg.)	-1,69	-4.506	24	0.000
Grip width (m)	0,08	3.558	24	0.002

Correlations to the energy conversion ratio were explored similarly as for the general model (Table 10). Statistically significant correlations were not found for either of the groups. In men, weaker correlations were found with step length ($r = -0,421$, $p = 0,118$), take-off angle ($r = -0,414$, $p = 0,125$), take-off velocity change ($r = 0,468$, $p = 0,079$) and pole angle ($r = 0,446$, $p = 0,095$), and in women with step length ($r = -0,564$, $p = 0,071$), step length ratio ($r = 0,464$, $p = 0,150$), take-off technique ($r = -0,391$, $p = 0,235$) and pole angle ($r = 0,536$, $p = 0,089$).

TABLE 10. Correlations to the energy conversion in men and women.

	SL	SR	SLR	TO technique	TO angle	TO vel change	CoG ratio	Pole angle	Grip width
Energy conversion (Men)	-0,421	-0,131	0,032	0,236	-0,414	0,468	-0,129	0,446	0,157
Energy conversion (Women)	-0,564	0,091	0,464	-0,391	0,255	0,309	-0,273	0,536	0,064

Multiple linear regression was created for both men and women using same variables as with the general model in table 10. Men's multiple linear regression ($R^2 = 0,752$) coefficients and standardised coefficients are in table 11 and comparison of predicted values and the real values in figure 24. Women's multiple linear regression ($R^2 = 0,984$) coefficients and standardised coefficients are in table 12 and comparison of predicted values and the real values in figure 25.

TABLE 11. Linear regression coefficients for men

Variable	Coefficient	Standardised Coefficient
Constant	3,491	
Step length	-0,300	-0,561
Step rate	-0,119	-0,407
Step length ratio	0,163	0,271
Take-off technique	0,034	0,834
Take-off angle	0,001	0,026
Take-off velocity change	0,962	0,799
CoG to reach ratio	-2,204	-0,565
Pole angle	0,000	0,005
Grip width	-0,137	-0,191

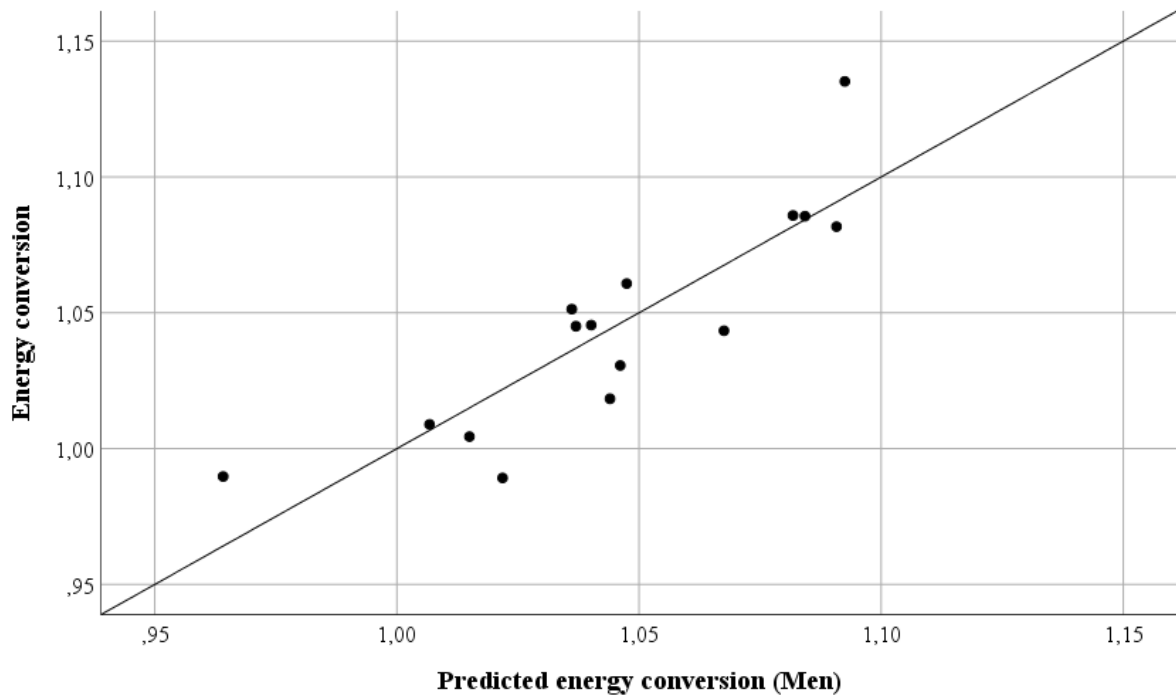


FIGURE 24. Scatter plot and reference line of predicted energy conversion and actual energy conversion for men.

TABLE 12. Linear regression coefficients for women

Variable	Coefficient	Standardised Coefficient
Constant	3,092	
Step length	-0,538	-1,673
Step rate	-0,199	-1,280
Step length ratio	0,413	0,533
Take-off technique	0,015	0,431
Take-off angle	0,001	0,055
Take-off velocity change	1,646	0,978
CoG to reach ratio	-0,169	-0,054
Pole angle	0,026	0,623
Grip width	-0,346	-0,501

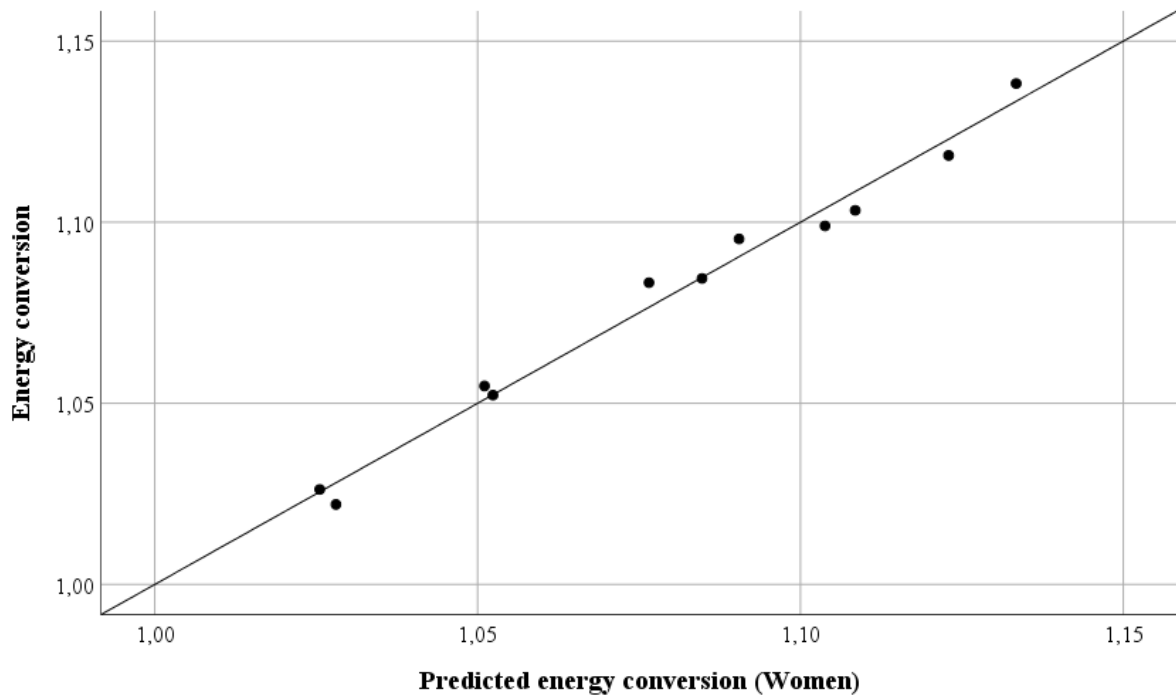


FIGURE 25. Scatter plot and reference line of predicted energy conversion and actual energy conversion for women.

Comparison of the standardized coefficients between energy conversion predicting multiple linear regression models (general, men and women) is in figure 26. Comparing the coefficients by absolute values between groups is not useful, but coefficient distribution between variables within the group gives the most useful results. Women's energy conversion was the most affected by the velocity as it was indicated by the large negative weights in step length and step rate (determinants of velocity), which was not the case in men. Both men and women benefitted from larger valued take-off technique and minimal velocity decrease, but men gave more weight to the take-off technique and women to the velocity maintenance. Greater distinguishing factors between men and women were women benefitting from larger pole angle (determinant of lower grip height) and men benefitting from a lower ratio of the centre of gravity height to reach height which both were non-existent in others. Narrower grip width had marginal benefit to the energy conversion, which was more visible in women than in men and the reduction in last step length does not seem to affect the energy conversion

positively, and women’s energy conversion even benefitted when last steps were close to an equal length.

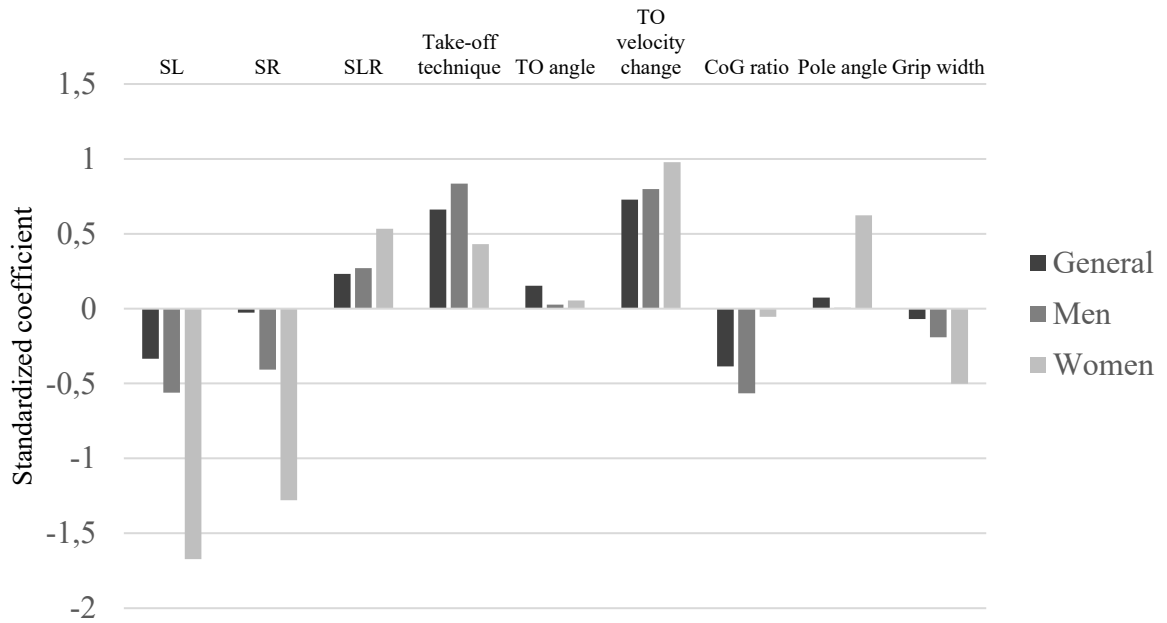


FIGURE 26. Comparison of the energy conversion linear regression models (general, men and women) standardized coefficients. Standardised coefficients are the relative coefficients obtained when variables are all transformed into standard scores that allow then the comparison between the relative strengths between coefficients. Note that it is not worth comparing the values of the standardised coefficients between models but their relative differences.

9 DISCUSSION

9.1 Method evaluation

The motivation to conduct this study was to use modern neural network-based motion recognition to produce usable and comparable data which could speed up sport research under the field conditions. 3-pixel difference between manually recognized landmark position and the neural network recognized landmark position could be considered as an adequate result. The combination of data correction and filtering produced a consistent kinematic result comparable to the manual recognition. 3-pixel distance converted to the real-world distance ranges from 3-4 cm depending on the location in a frame and which camera was used.

Even though there were a lot of significant differences between the observed values and the reference values, most differences were small and consistent. The reasons behind these small differences could be explained with differences in calibration procedures, systematic differences in landmark recognition, lower video resolution or in the use of two-dimensional analysis in this work. One possible source of error identified was with the calibration frames. The locations of the calibration frames in relation to planting box was not known, so those had to be estimated using the markings from the track and determined by experimenting with all near values to minimize the error in a direct linear transformation. The cameras had also slight movement in between calibration frame shots and shots from the competition, so the camera views had to be aligned to improve the accuracy. Despite these problems, observed values and reference values largely corresponded to each other.

On the other hand, horizontal plant velocity, take-off angle and pole angle at take-off had large differences compared to the reference. Judging by the velocity curves and the fact that runway and take-off velocities had results more in line with the reference, the reason appears to be mostly the differences in the identification of the pole plant moment. Resultant velocity and horizontal velocity at take-off showed similar values as the reference, but these small differences led to larger differences in take-off angle (i.e. the direction of the resultant velocity vector). To calculate the angle of the pole at take-off, there does not seem to be clear

indicator where the differences are coming from and it is likely that differences are due to the way the angle is calculated. Therefore, the accuracy of the method in many cases is similar compared to the reference. Some systematic differences occurred as it could be expected, and the largest differences and variances were most likely due to differences in calculating the values, not the method itself.

9.2 Analysis of run-up and take-off variables

The combination of run-up variables varied from an individual level which was indicated through correlations being sub 0.4 between step length, step rate and the reduction of last step length. As it would make sense, some athletes used shorter step length and higher step rate to produce the velocity needed and vice versa. Since the run-up variables were explored in an average level instead of every step, individual patterns of running regulation from Needham et al. (2018) were not recognized but were probably present in the competition.

From the take-off variables, most significant correlations focused on plant timing, take-off position, velocity change from run-up to plant and from plant to take-off, vertical positional centre of gravity change from plant to take-off, ratio of the centre of gravity and reach height, and pole bend from plant to take-off. Take-off angle, pole angle and grip width did not seem to correlate significantly with other take-off variables apart from negative correlation between the pole angle to the ratio of the centre of gravity and reach height. Grip width was selected to the variables because it was hypothesized to affect the athlete's choice of take-off position and plant timing, but this seemed not to be the case and to be only the preference of an individual athlete. Pole angle and take-off angle were surprisingly left out of the correlating take-off variables. Pole angle might be more determined by the grip height and thus not be part of the take-off features. Take-off angle on the other hand was more of a surprise, and that might be one take-off variable that athlete has some influence on regardless of the other take-off properties. Finding is similar with Schade et al. (2012) who discovered that take-off angle remained similar regardless of the pole plant timing and varied according to the skill level.

The four correlating take-off variables which were thought to be due to the same technical model and in relation to each other (plant timing, take-off position, pole bend before take-off and vertical centre of gravity change from plant to take-off) were chosen to the principal component analysis to explore if the correlations could be explained with more comprehensive component. As it turned out, the component found explained close to 90% of the variations between correlating variables. Results were used to create standardized numerical value between -1,88 and 1,76 for the combination of these variables. Schade et al. (2012) classified vaulters similarly to early, intermediate, and late classes according to their plant timing, and the results were similar as well since earlier pole plant and take-off position being closer to the planting box (i.e. greater values in take-off technique) led to a more energy transfer from vaulter to the pole during the take-off. Similar finding in this study was that pole bends more between plant and take-off (i.e. kinetic energy is transferred to the pole) when greater values in take-off technique. Also in this study, centre of gravity height and its ratio to the reach height increased more when athlete performed an early plant, which is probably due to the reaction force from the pole plant deforming the body (Linthorne 2000) and same time pushing the centre of gravity upwards (Angulo-Kinzler et al. 1994). Additional finding for take-off technique was that when take-off technique had lower values (late plant from Schade et al. 2012), horizontal velocity starts to decrease even before the pole plant. This might be due to negative work done by the contacts ground reaction force, kinetic energy transfer to rotational kinetic energy, or just be a by-product of the data filtering, so more research would be needed to draw further conclusions.

Comparing differences between men and women, most variables got similar values on average. Both men and women had similar step rates, but men used longer step lengths in their running which is the main differentiating variable for the faster velocities measured in this competition compared to women. Men used on average wider grip width than women, but in proportion to other anthropometric features the difference probably would not have been noticeably different. Only take-off related difference between men and women was the women's choice of higher pole angle at take-off. Pole angle is an indicator of lower grip height, which can be used with stiffer poles to gain more energy return from the pole to increase athletes push height (Ekevad & Lundberg 1995). Since men used lower pole angles, their grip heights were relatively higher compared to women. This might be one factor why

on average women had slightly better energy conversion because use of a too high grip could impair performance (Linthorne 2000).

Energy conversion ratio was chosen for the performance metric in this study. It was calculated as the ratio of potential energy at the level of a cleared crossbar and mean kinetic and potential energy during the mid-section of the runway. It was used to create linear regression model in combination with runway velocity that predicted the height cleared by an athlete with minimal difference, so its use as performance factor was justified. A clear disadvantage for this was that the metric did not consider how much potential energy was actually achieved, or how much kinetic energy was left to use as athletes flight path over the bar. On the other hand, it can be used as a variable of how much of the kinetic energy on the runway has been used effectively to clear the bar. So if the value is higher, an athlete uses its available kinetic energy better versus an athlete with lower value. Energy conversion behaved within the groups so that the slower athletes had better energy conversion and faster athletes worse regardless of the absolute runway velocity. That means that even though the relationship within the group behaves linearly, the relationship cannot be generalized.

9.3 Performance determining characteristics

The two most determining factors to the better energy conversion in a multiple linear regression model which included both men and women were horizontal velocity change during the take-off and take-off technique. Horizontal velocity change correlated positively to the energy conversion which means in practice that less the velocity decreases during the take-off the better. Take-off technique did not correlate by itself to the energy conversion, but the linear model preferred higher valued take-off techniques (i.e. early plant). Since the higher valued take-off technique also starts to impair horizontal velocity maintenance, earlier plant could not be directly recommended. Probably the best combination would be as early plant as possible which can still maintain adequate horizontal velocity. Hypothesis to the first research question of what factors influence athlete's performance in a competition was that minimal horizontal velocity loss and centre of gravity increase at take-off would result to a better energy conversion. For the velocity loss, the hypothesis can be confirmed directly as the

variable had the largest standardized coefficient. The centre of gravity increase was baked into the take-off technique variable and higher values indicated higher centre of gravity height increases, so the hypothesis to the second part can be accepted but should be noted that it is part of the larger take-off technique complex. Plant timing has previously not been noticed to influence the total amount of energy transfer through the take-off (Schade et al. 2012) so the benefits of the higher valued take-off technique could be seen in the free flight phase. The reason why the energy conversion is better with early plant could potentially be due to bending moment produced during the take-off contact (Morlier & Mesnard 2007) that maintains total energy level and facilitates the energy adding actions in later parts of the jump.

The first hypothesis to the second research question of how factors differ between men and women was that women's performance would benefit from a higher grip achieved using lesser stiff poles. The hypothesis was based on a women's more limited technique at the end of the jump such as lack of free flight phase and height increase caused by it (Grabner 1997; Gravestock et al. 2017a; Gravestock et al. 2017b) in which case athlete would benefit from a higher grip height. The determining variable for a high grip would be lower pole angle and for less stiff pole a good horizontal velocity maintenance during the take-off. The hypothesis can be rejected in this regard since women's energy conversion benefitted from higher pole angle (i.e. lower grip height) and higher valued take-off technique (early plant) which correlates to higher velocity loss after the pole plant. Lower grip in combination with stiffer pole increases the achievable push height (Linthorne 2000) and could potentially be the reason why these factors increase the energy conversion in women.

Second hypothesis to the second research question was that men would allow more horizontal velocity loss after the pole plant due to the use of stiffer poles (Linthorne 2000). The answer must be approached from the take-off technique perspective since larger valued technique would result to a more velocity loss after the pole plant. The hypothesis can be partly accepted since the larger valued take-off technique was greater determinant than take-off velocity compared to the opposite finding in women. There were also some mixed coefficients from a ratio of the centre of gravity and reach height, and pole angle. However, other variables make a greater difference between men and women such as women's greater impairment of the energy conversion when velocity determinants (step rate and length) are high. It would seem

that approach velocity affects to the energy conversion more in women than in men, but actually energy conversion decreases similar rate as the velocity increases for both men and women (Figure 23). Thus, it would appear that in women, velocity decreases the energy conversion regardless of the technique, but in men the decrease would come from the higher velocity impairing execution of the effective take-off.

9.4 Strengths and limitations of the research

The most significant advantage to this study was the use of modern neural network-based markerless motion recognition as the first implementation in a real-world pole vault competition research, and possibly the first implementation in the whole athletics spectrum. This led to a significant reduction in labour cost of recognition since the accuracy was achieved with 6-7 manually labelled frames/athlete/camera which corresponded to a under 5% of the total frames used. Possible sources of error in motion data were unknown location of the calibration frame, misalignment of calibration shots compared to the competition, and the manual labelling was done by inexperienced labeller without supervision or inspection from more experienced labeller. Although the observed accuracy was fine, a more controlled setup would be needed to do proper validation. All athletes jumped with same foot in which case there was no need to consider identifying the opposing technique but could affect difficulties to the recognition.

Major limitation considering the energy conversion models was the inability to measure angular momentum. For some athletes there was only one view available, so the position of the opposite side hip and shoulder marker had to be the same as on the other side. Since the opposite hips and shoulders swing forward and backward in the opposite rhythm, their position being the same lead to a slight forward-backward-swing motion of the upper body. Impact on angular momentum was too high to be used, but impact on other variables such as centre of gravity position was not observable. The ability to use angular momentum as one variable during the take-off might have had an impact on energy conversion models and would be a good addition if take-off properties are studied more in the future. Other model limiting factor was the lack of pole stiffness since it could not be measured and could have

had an impact to energy conversion or some variables for example velocity decrease during the take-off.

Energy conversion as a performance metric was an advantage to this study compared to some other studies since it eliminates the effect of velocity and allows a direct comparison of men and women. On the other hand, only one competition was used and not all athletes achieved their best performance, and the metric did not take this into account. The relationship between energy conversion and cleared height or success in a competition was intentionally left out from this study to highlight the energy conversion. However, it can be said that considering the negative correlation between runway velocity and energy conversion, the winning athletes were not the ones with the best energy conversion value. Also, they were not always the fastest. Improvements to achievable heights could be found from the ways to maximize energy conversion from high approach velocities and thus be studied more.

The significance and generalizability of the results were mainly influenced by the data limiting to only one competition. For some athletes, the cleared heights did not represent their true potential and certainly affected to the coefficients of the models. However, the results could be said to describe well the real competition circumstances with over and underperformers. The results are applicable to only elite athletes since the data included only the best athletes at the time but can provide information to less advanced groups on where the focus should be at take-off.

9.5 Conclusions

This study showed that DeepLabCut and similar markerless image recognition software are suitable for extracting meaningful information from a competition setup without needing skin-attached markers or high-end cameras. Markerless methods have also the potential to be used in a pole vault and athletics research, but more controlled validation would be beneficial. Since the labour cost of doing research with the help of modern technology would be lower, further studies should be carried out with more athletes to increase the significance and generalizability of the findings.

Women's and men's ability to transfer energy from the run-up to the potential energy effectively is similar and on average even better for women in this competition, so the performance difference between men and women is mostly explained by the differences in horizontal velocity at least in top level. Men used relatively higher grip heights than women, but the effect to the gained energy from run-up to the cleared height is non-existent. Also, the energy conversion ability decreased as the velocity increased so in the future a superior athlete might be the one that could maintain an effective take-off technique despite being the fastest.

Energy conversion benefitted at take-off from early plant, top grip being horizontally behind take-off foot tip, and centre of gravity height increasing and pole bending from plant to take-off, but only when combined with good horizontal velocity maintenance. In addition to that, energy conversion was more negatively affected by the velocity determinants in women than in men whose performance gave more emphasis on previously mentioned take-off technique. However, positively and negatively influencing variables were either the same direction or non-visible in the other group so the technique could be considered to be the same in men and women.

Further studies in pole vault should focus on detailed examination of phases and the connections between them. The focus should be in increasing the number of athletes used in studies as well as determining the effect of different anthropometric features and their impact to the optimal technique.

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APPENDICES

APPENDIX 1. Data integrity. X = used, - = missing and O = invalid.

Athlete	Sex	Camera 1	Camera 2
1	Male	O	X
2	Female	X	X
3	Male	X	X
4	Male	X	X
5	Male	X	X
6	Male	X	X
7	Female	-	X
8	Male	-	X
9	Male	X	X
10	Male	-	X
11	Male	X	X
12	Female	X	X
13	Male	X	X
14	Male	X	X
15	Male	-	X
16	Female	X	X
17	Female	X	X
18	Female	X	X
19	Female	X	X
20	Female	X	X
21	Female	X	X
22	Female	X	X
23	Female	X	X
24	Male	X	-
25	Male	X	X
26	Male	X	X

APPENDIX 2. Descriptives of variables used in the pole vault performance analyses.

MEN

Variable	Mean	Std	Min.	Max.
CoG vertical change from plant to take-off (m)	0,104	0,033	0,040	0,150
Ratio of centre of gravity and reach height	0,545	0,010	0,530	0,570
Grip width (m)	0,660	0,057	0,550	0,770
Plant timing (ratio)	0,521	0,238	0,140	0,910
Velocity change from plant to take-off (ratio)	-0,081	0,054	-0,160	-0,010
Pole angle (deg.)	29,809	0,979	27,920	31,100
Pole bend ratio	0,031	0,017	0,010	0,070
Runway velocity (m/s)	9,297	0,209	8,930	9,750
Step length (m)	2,144	0,076	2,020	2,270
Step length ratio	0,954	0,068	0,860	1,100
Step rate (steps/s)	4,504	0,139	4,290	4,800
Take-off angle (deg.)	17,818	1,668	13,940	20,210
Take-off position (m)	-0,361	0,232	-0,740	0,050
Velocity change from run-up to plant (ratio)	-0,083	0,037	-0,140	-0,030

WOMEN

Variable	Mean	Std	Min.	Max.
CoG vertical change from plant to take-off (m)	0,092	0,037	0,020	0,150
Ratio of centre of gravity and reach height	0,538	0,012	0,520	0,560
Grip width (m)	0,582	0,054	0,520	0,700
Plant timing (ratio)	0,552	0,268	0,090	1,000
Velocity change from plant to take-off (ratio)	-0,077	0,049	-0,140	-0,010
Pole angle (deg.)	31,498	0,894	30,010	32,950
Pole bend ratio	0,033	0,014	0,010	0,050
Runway velocity (m/s)	8,163	0,228	7,890	8,540
Step length (m)	1,897	0,115	1,720	2,070
Step length ratio	0,937	0,048	0,880	1,020
Step rate (steps/s)	4,480	0,238	4,110	4,840
Take-off angle (deg.)	18,590	2,290	14,720	24,090
Take-off position (m)	-0,299	0,249	-0,670	0,110
Velocity change from run-up to plant (ratio)	-0,078	0,034	-0,130	-0,030