GÖTEBORGS UNIVERSITET
INST FÖR KOST- OCH IDROTTSVETENSKAP

Determination of biomechanical key parameters in women's long jump

An analysis of Swedish elite athletes in a competitive setting

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Kandidatuppsats 15 hp
Program: HP-idrottsvetenskap
VT2015
Handledare: Tobias Hein
Examinator: Jesper Augustsson
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Summary:

Long jumping technique has been widely studied both on elite athletes and with models made for determining optimal techniques. However studies looking at women long jumping are scarce and there is still no consensus regarding which variables are the most important for determining long jumping performance. The purpose of this study was to determine how established key variables in the long jump affect performance for women elite long jumpers. Key variables were identified based on previous studies and analyzed regarding correlation with and prediction of jumping distance. 2-D high-speed video of the women long jumping final in the Swedish national championship 2014 was evaluated and a total of 33 jumps were digitized. Regression analysis resulted in run up speed being the most important variable explaining 40% of jump distance. Other important variables significantly related to a longer jump distance was; a loss in mechanical energy, a shorter toe-board distance, bigger height change in centre of mass, lower maximum knee flexion and a shorter contact time. By including one variable from each of the categories speed, accuracy and technique a multiple regression model could explain 55% of the jump distance. As a conclusion run up speed appears to be the most important variable differencing the best athletes from the rest, however different technique parameters still influence the individual performance greatly.

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Sammanfattning:

Längdhoppsteknik har undersökts i ett flertal studier där både elitidrottare testats och olika modeller skapats för att kunna bestämma den optimala tekniken. Studier som undersöker kvinnliga längdhoppare är dock få och det råder dessutom ingen konsensus kring vilka variabler som är mest viktiga för en optimal längdhoppsprestation. Syftet med denna studie var att bestämma hur nyckelvariabler påverkar längdhoppsprestation hos kvinnliga längdhoppare på elitnivå. Viktiga längdhoppsvariabler identifierades genom en bakgrundsanalys av tidigare studier där dessa variabler sedan blev analyserade statistiskt gällande relation med och förmågan till att förutsäga hopplängd. 2-D höghastighets video från längdhopps SM 2014 analyserades och totalt blev 33 hopp överförda digitalt. En regressionsanalys visade på att löphastigheten fram tills hoppet var den absolut viktigaste variabeln, där detta kunde förklara 40 % av hopplängden. Andra viktiga variabler som ledde till en längre hopplängd var; förlust av mekanisk energi, kortare distans mellan tå och bräda, större höjdförändring av kroppens masscentrum, lägre maximal knäflektion och kortare kontakttid med marken. En modell bestående av en hastighet, en träffsäkerhets och en teknik variabel kunde förklara 55 % av hopplängden. Slutsatsen var att löphastighet fram tills hoppet är den viktigaste variabeln som skiljer de bästa atleterna från resten, dock verkar det som om individuella teknikparametrar ändå påverkar den slutgiltiga hopplängden till en väldigt stor del.

Foreword

First and foremost we would like to give our gratitude to Stefan Grau and Tobias Hein for introducing and inviting us to write this study in the long jumping project at KHP, Center for Health and Human Performance. Tobias unlimited and always very prompt support has been admirable throughout the whole process. Furthermore we are both very thankful for the fact that we were invited to spend our time writing and performing our work at the premises of KHP, it has been a great possibility and a big learning experience for both of us. Finally we would also like to give our best regards to Jesper Augustsson and Mathias Wernbom for being patient with our long jumping conversations and chit-chatting at the office.

Arbetsuppgift	**Procent utfört av Daniel/Mikael**
Planering av studien	50/50
Litteratursökning	50/50
Datainsamling	50/50
Analys	40/60
Skrivande	50/50
Layout	40/60

Innehåll

Introduction

Long jumping is a well-recognized discipline within the track and field sports and it has been a part of the Olympic Games since the re-start of the modern games in Athens 1896. Physical performances such as jumping has always fascinated and a more specific athletic performance such as the standing long jump is often used as a reference for adapting to adequate training programs and when measuring explosive leg power (Wakai & Linthorne, 2005). The scientific work in the field of jumping, regardless if it's high or long jump, have over decades mapped out and explained certain parts of this athletic performance. Studies range from the dynamics behind the actual muscle extension/flexion phases and the contribution from tendons, to studies of the single most influential technique parameter in the long jump; for example velocity and forces acting on the jumper (Seyfarth, Friedrichs, Wank, & Blickhan, 1999; Bridgett & Linthorne, 2006).

Studies have examined and strived to determine the optimum angles in different parts of the leg as well as examining the most effective touch-down and take-off angles (Wakai et al. (2005); Guzman, Bridgett, & Linthorne, 2005). Current key variables for the long jump are regarded as speed, specific technique variables affecting the jump and muscle strength (Graham-smith & Lees, 2005). Even though there is a unanimous agreement among several of these key variables affecting the long jump in the current scientific literature, there still lies a challenge in understanding the complete picture and possible interrelationships between factors related to a successful long jump. Studies by Graham-Smith et al. (2005) and Bridgett et al. (2006) used multiple regression analysis in order to better understand the relationship between technique variables and long jumping performance. Their multiple regression models could however only slightly or moderately improve prediction strength and as a result the interrelationship between technique variables is relatively unknown.

The gathered long jumping data from the selection of studies presented here are collected from a broad variety of differently skilled athletes, from ”physically active” people (Linthorne, 2008) or school students (Seyfarth, 1999; Seyfarth, Blickhan & Van Leeuwen, 2000) to top international long jumping athlete performers (Guzman et al., 2005; Hay, Miller & Canterna, 1986). In this study the subjects are Swedish female professional long jumpers. They are all currently competing on the national level and the gathered raw-data presented here was captured during the Swedish national championship in early 2014. Only one previous study by Lees, Fowler & Derby (2007) could be found investigating female athletes on a top national level and under competitive conditions. Consequently this study focuses on providing further data in the field of women long jumping in an elite competition setting. The goals of this study was not to present new variables related to the long jump, but rather determine relationships and prediction strength between current established key variables and long jump performance. Further data collections on Swedish national athletes, especially women athletes, are also of use for involved federations. An explanation of terminology and abbreviations used in this study can be found in the appendix (Appendix 1).

Purpose

The purpose of this study was to determine how established key variables in the long jump affect performance for women elite long jumpers.

Research questions:

The following questions were focused in order to evaluate the key variables affecting the performance of a long jump.

i. What relationship exists between key variables and jump distance?
ii. Which key variables can predict jump distance?
iii. Can multiple regression analysis improve predictions of jump distance?

Scientific Literature Overview

It is well known today that in order to execute a good performance in long jumping there are a few essential components which will have a larger effect on the length of the jump than other mechanisms. The most important factor appears to be the run up speed and the horizontal velocity achieved by the athlete before and during take-off. For example studies by Alexander (1990); Hay & Nohara (1993); Lees, Graham-smith & Fowler (1994) point out that for a successful jump the athlete need a large horizontal speed, achieved during the run up phase of the jump. Both the athlete´s ability to generate a high horizontal velocity in combination with vertical velocity between touch-down and take-off is of great importance when it comes to optimizing performance in the long jump (Bridgett et al., 2006; Wakai et al. (2005); Graham-smith et al., 2005; Seyfarth et al., 2000; Hay et al., 1986; Hay, 1993).

However the relationship between horizontal and vertical velocity is complicated. A large horizontal velocity shortens the contact time the athletes has with the ground and as a consequence restricts the generating of vertical velocity during take-off. Generation of vertical velocity is on the other hand required through the touch-down and take-off phases in order to give the athlete altitude and time in the air. To increase the ground contact and aid the generation of vertical velocity, the athlete places the foot further ahead of the center of mass during the touch-down phase, creating a shallow leg angle at touchdown. However this leads to a reduction in horizontal velocity, creating a negative horizontal impulse. Consequently vertical velocity is necessary for height in the jump and horizontal velocity for jump distance and the trade-off between horizontal and vertical velocity is of great importance for a successful long jump (Alexander, 1990; Seyfarth et al., 1999; Linthorne, 2008; Bridgett et al, 2006).

The take-off angle is another important factor affecting the long jump and it is exclusively determined by the athletes combined vertical and horizontal velocity during the take-off phase. The long jump could be seen as a projectile in free flight where an increase in run up speed should lead to a greater jump distance. For a projectile in free flight and with constant speed a release angle of 45°will reach maximum flying distance. Theoretically the optimum take-off angle for a long jumper would be at 45°, similar to an object in free flight with equal forces acting on the object´s horizontal and vertical axis and without any braking forces acting on it at launch or take-off. However this take-off angle is not plausible in terms of long jumping since the basic physiology of the human body is designed to facilitate horizontal movement and acceleration rather than achieving vertical forces. An athlete can produce a greater horizontal velocity with a higher run up speed (around 10 m/s) than vertical velocity from the jumping action during take-off (max around 4m/s), resulting in an angle lower than 45 degrees for the long jump (Wakai et al. (2005); Bridgett et al, 2006; Guzman et al., 2005).

It is possible to try and force a larger take off angle as shown in studies by Wakai et al. (2005) and Guzman et al. (2005), however the results show a large performance decrease as a consequence of the reduction in horizontal velocity needed for take-off angles greater than 30°. Another, yet less influential, aspect that is working against the theoretic take-off angle of 45° is the height of the centre of mass at take-off in relation to the height centre of mass at landing is not equal in a long jump (the height of the centre of mass is lower at landing compared to the height at take-off) which results in a lower optimum take-off angle for the long jump (Wakai et al. (2005).

The necessity for an optimum take-off angle and a successful long jump can be discussed. Guzman et al. (2005) describes that the performance in take-off angle and flight distance are strongly related and states that in order to achieve a jump within 5 cm of the athletes' calculated maximum distance it is necessary to stay within a 1° margin of the optimum take-off angle. On the other hand Hay et al. (1986) found no correlation between take-off angle and flight distance (r=-0.05). A suggestion could be made that an optimum Take-off angle might not be completely decisive for the performance of individual athletes. Regardless of the impact take-off angle has on long jump performance a common understanding in the current scientific literature is that take-off angle is largely determined by horizontal and vertical velocity and as a results speeds higher than >8m/s will produce a take-off angle around 10-20^o (Graham-smith et al, 2005; Bridgett et al, 2006; Seyfarth et al., 2000).

Most of the available studies today are comparing different athletes long jumping techniques with theoretically developed models. For example a strict theoretic mechanical model that quantitatively outlines the center of gravity and its dynamics during the long jump is used by (Seyfarth et al., 1999). Seyfarth et al., (1999) propose a model with relatively few components to explain the dynamics behind the long jump and also argue that the high run up speeds in long jumping and the jumping dynamics, directly at the start of the touch-down phase, contributes with 1/4th of the total momentum in long jumping.

The model of Alexander (1990) concludes that the longest jump is obtained with a leg angle at 70^o and the highest possible run up speed (11 m/s is reported as the highest speed in the model). An improved model by Seyfarth et al. (2000) suggests an optimal leg angle (angle of attack) between 65-70^o. However Seyfarth et al. (2000) also conclude that leg angle was relatively insensitive for run up speeds higher than 6 m/s which indicate that a leg angle of 65-

70^{o} might be the most efficient leg angle, but not decisive for a good performance. A higher run up speed could compensate for a lower leg angle and lead to the same result as the most efficient/optimal leg angle.

Studies have not only looked at how variables correlate with and predict jumping distance but also if there are possible interrelations between variables affecting the long jump. Bridgett et al. (2006) investigated the knee angle at touchdown and found an increase in knee angle at touchdown with a higher run up speed and conclude that a higher knee angle at touchdown is beneficial to prevent excessive flexion of the knee. This prevention of knee flexion could also promote a straighter leg during the jump phase, allowing the centre of mass to pivot over the take-off foot, resulting in a greater vertical velocity and longer jump distance. A study conducted by Graham-Smith et al. (2005) shows a greater knee extension at touchdown was found to be related with less knee flexion ($r=-0.598$, $P< 0.05$) and also to a higher vertical velocity ($r=0.584$, $P<0.05$) indicating that a straighter knee could be beneficial for a better performance.

Graham-smith et al. (2005) also suggest that in order to have a greater gain in centre of mass height, a low position at touchdown and a high upright position at take-off is needed. Leg placement during touchdown and arm and leg movement during take-off could be an important factor for a greater gain in centre of mass. However a conclusion is made that gain in centre of mass height probably has an optimum value since a greater centre of mass difference is related to an increase in loss of horizontal velocity but also an increase in vertical velocity gain. Therefor an optimum value for the centre of mass height gain lies between a compromise of vertical velocity gain and horizontal velocity loss.

Gain in vertical velocity by itself appears to be connected with the variables of centre of mass height, knee angle at touchdown and the ability to resist knee flexion. Graham-Smith et al. (2005) found a coefficient of determination of 78.8% for knee angle at touchdown, centre of mass height at touchdown and peak knee flexion velocity (a low peak value was seen as the ability to resist knee flexion) and vertical gain during the take-off phase.

The contact time the athlete has with the ground during the touchdown-take-off phase could be an important factor for a successful long jump performance. Bridgett et al. (2006) report a decrease in contact time with increasing run up speed, although the rate of decrease is not linear since the athlete will compensate for the lowered contact time by planting the foot further ahead. A relationship between a lowered leg angle and an increase in run up speed is proposed where the athlete is required to plant the leg farther ahead (resulting in a lower angle) in order to increase the contact time with the ground. A lower take-off angle as result of a higher run up speed will also cause the take-off leg to make a greater angle at the instant of take-off, resulting in a larger range of motion and extended contact time. Bridgett et al. (2006) also report a range of motion of the take-off leg of about 60^{o} at run up speeds of 11 m/s, and 40^{o} at 5 m/s indicating that leg range of motion and run up speed is connected to contact time.

Additionally a special variable is that of toe-board distance, which is measured as the distance between the foot and the jumping board. This variable could be seen as a depiction of accuracy for the individual athlete; where a shorter toe-board distance is beneficial. Although this variable has not been widely analyzed, both Hay et al. (1986) and Hay (1993) discuss the importance of this variable where accuracy could affect other variables during the run up. For instance horizontal velocity at touchdown could be affected, where the athlete has to sacrifice horizontal velocity in order to assure accuracy. Consequently toe-board distance could play an important role for a successful long jump.

The technique variables affecting the long jump appear to be connected with each other creating a complex system to analyze. To better understand how technique affects the long jump and to better map out important technique variables, the implementation of a multiple regression analysis is of much use. Only a few studies have used multiple regression analysis to try and understand the possible interrelations between variables for predicting a successful long jump performance. Bridgett et al. (2006) used multiple regression analysis to evaluate the effects knee angle and leg angle had on predicting jump distance in combination with run up speed. The created multiple regression model of run up speed, knee and leg angle was found to only slightly improve the prediction, compared to run up speed on its own which already predicted 96%. . Graham-smith et al. (2005) reported a correlation coefficient of $r=0.496$ ($p>0.05$) between run up speed and flight distance and a coefficient of determination of $R^2 = 24.6\%$. By adding the technique variables of height change in centre of mass and change in resultant velocity during touchdown-take-off to run up speed in a multiple regression analysis the coefficient of determination increased to $R^2=65.5\%$. The conclusion was made that a technique that encourages a reduced loss of speed and a greater gain in height of the centre of mass during the jump phase in combination with a high run up speed is related to a longer flight distance.

As a result of the literature review the following 18 key variables were identified and selected based on previous suggestions, correlations and predictions reported with long jump performance: Horizontal and vertical run up speed at touchdown and take-off, change in mechanical energy, change in horizontal and vertical velocity, leg angle at touchdown, knee angle at touchdown, toe-board distance, maximum knee flexion, height change of the centre of mass, take-off angle and contact time.

Figure 1 is a model showing key variables and simple connections between variables. The model is not intended as a hierarchical model but rather to show the relationships between variables: For example mechanical energy is composed by change in resultant velocity at touchdown and take-off but mechanical energy is not intended to be superior to resultant velocity in predicting official distance.

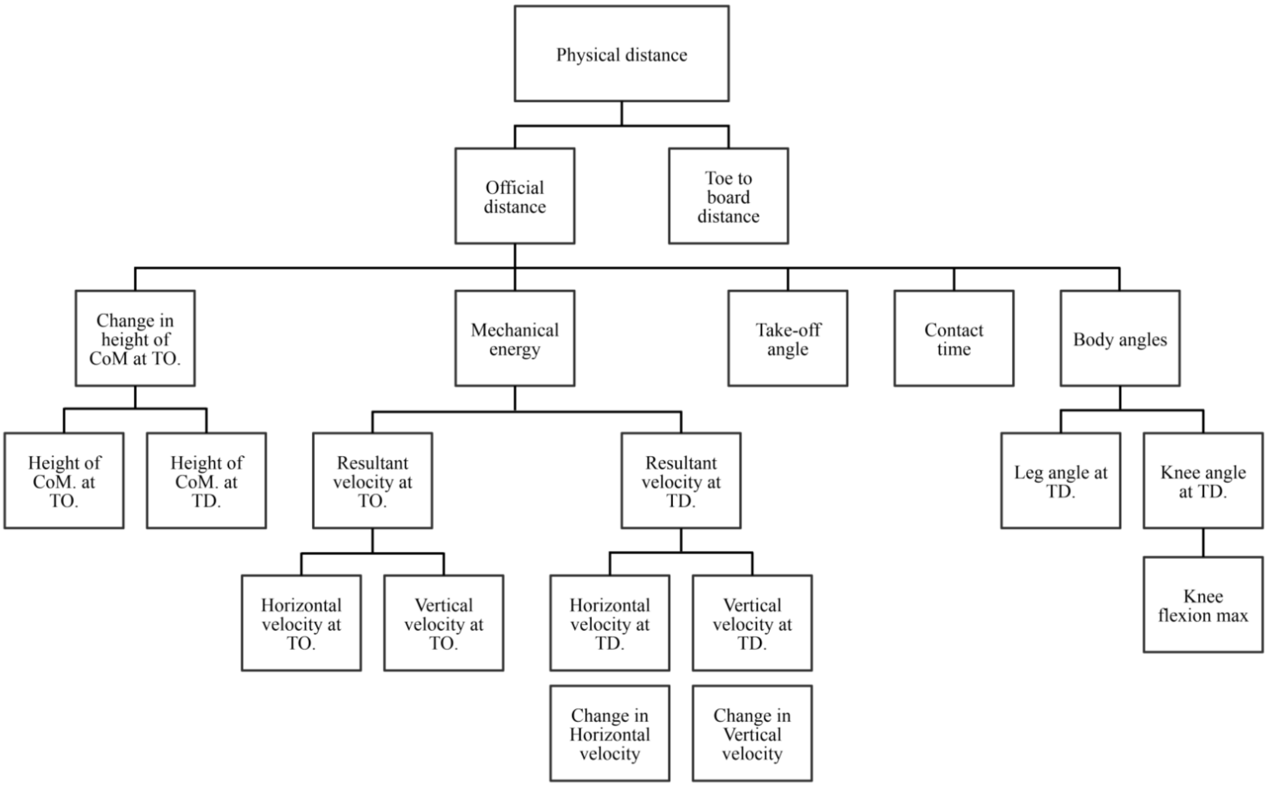

Figure 1. Model for key variables (based of Hay et al. (1986) theoretical model)

Method

Design

This study had an inductive approach in the field of long jumping. Variables were selected with a literature review and selected variables was digitized and computed from high-speed video footage. Using statistical tests key variables were determined based on their correspondence with long jumping performance. In order to fulfill the purpose set for this study an inductive approach based on a literature review was deemed necessary in accordance with Bryman & Nilsson (2011).

Literature review

The search for scientific literature was done using the website PubMed and three different searches were performed in total. Four articles were chosen based of a search containing the words "Long jump" + "angle" which generated 15 hits. The second search had a total of 13 hits with the keywords "long jump" + "biomechanics". The final search recorded a literature list of another 20 hits and generated one additional study to our list of references. This was received after combining the words "long jump" + "technique". Finally, a small number of studies were later included in this work by scouring through the reference lists of some of the chosen literature.

The findings in summary; three searches were conducted with a total finding of nine relevant studies, from which two documents were review-studies. The total amount of hits for the three searches was calculated to 48. Most of the non-relevant hits were neglected based on the study's name or after reading through its abstract. The combination of keywords was determined first and foremost after a discussion regarding the approach and the purpose of the study and also since this particular combination was found to provide a complete picture of the long jump.

Data acquisition

Previously recorded video of the women long jump final during the Swedish indoor national championship (ISM) 2014 was analyzed with regards to specific technique parameters. Data for body mass and length was not available. 2-D video of the touchdown and take off was captured using one Qualisys Oqus 3+ high speed video camera filming at 200Hz. The camera was placed 1.5m from the jumping board with the optical axis of the camera perpendicular to the long jump runway and the field of view of the camera showed only the athlete slightly before touchdown and after take-off. The camera setup was made not to disturb or affect the athletes during the jump and without disturbing any other part of the competition. Jumping distance was gathered using the official distanced measured from board to landing during competition. Only valid jumps were included (n=33). Aborted or invalid jumps were disregarded. The video was calibrated using the distance of the jumping board (20 cm) as a set reference point to convert pixels to meters. Involved officials during the competition were informed when the videos were captured; however the competitors were not aware of any recording. The Swedish Athletic Association and Göteborg friidrott who hosted the competition was also informed of the measurement. Anthropometrical information for body height, weight and age was not available.

Digitization of data

Qualisys video analysis (QVA, Version 3.7-009, Qualisys) was used for analyzing and digitizing of the video. Body landmarks was manually according to recommendations made by Dempster (1956), published in McGinnis (2013). Hence, the centre of mass (CoM), hip, knee, ankle and tip of foot of the jumping leg were digitized for each frame, creating a simple four segmental model of the athlete. Touchdown and take-off was defined where touchdown was the first frame where the foot had clear contact with the ground (Figure 2) and take-off the frame where the foot had clearly left the ground (Figure 3).

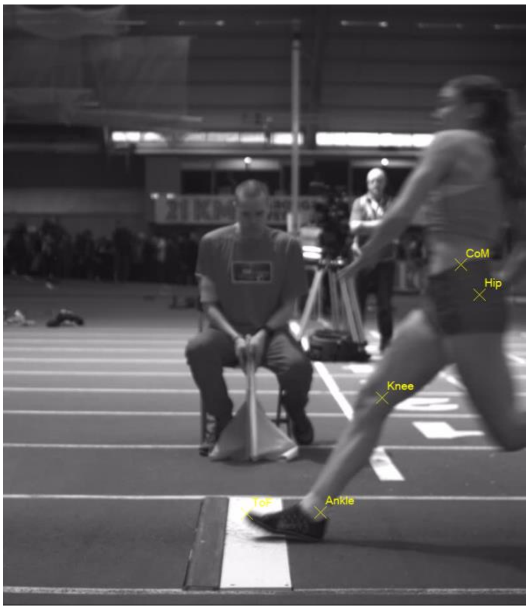

Figure 2. Touchdown frame with markers for tip of foot, ankle, knee, hip and centre of mass

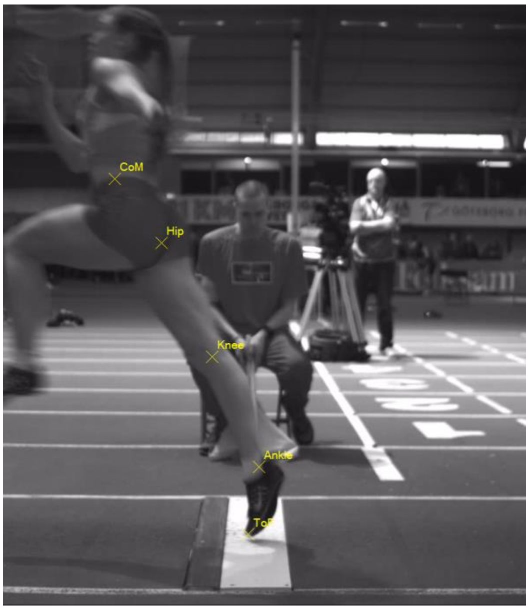

Figure 3. Take-off frame with markers

Calculation of variables

a) Distances

- Height of CoM at TD[cm]
  Distance between a reference point at the ground and the centre of mass body landmark. The set reference point was defined as the point of contact between the sole of the shoe and ground.

- Height of CoM at TO[cm]
  Distance between a reference point at the ground and the centre of mass body landmark, measured in cm at take-off.

- Change in height of CoM at take-off [cm]
  Difference in centre of mass height between touchdown and take-off.

- Toe to board distance [cm]
  Distance between the tip of the foot and the take-off board when the foot had reached full contact with the ground.

b) Velocity

- Resultant velocity at touchdown and take-off [m/s]
  Resultant velocity at touchdown and take-off.

- Mechanical energy [m/s]
  Difference between resultant velocity at take-off and the resultant velocity at touchdown.

- Horizontal and vertical velocity at touchdown [m/s]
  Velocity at touchdown frames.

- Horizontal and vertical velocity at take-off [m/s]
  Horizontal and vertical velocity components at take-off.

- Change in horizontal and vertical velocity [m/s]
  Difference in horizontal and vertical velocity components between touchdown and take-off.

c) Timing

- Contact time [s]
  The time the foot was in contact with the ground from touchdown to the take-off frame.

d) Angles

- Knee angle at TD. [°]
  Angle comprised by the hip, knee and ankle markers at the instant of touchdown. (Figure 4).

- Leg angle at TD [°]
  Angle formed by the segment of the knee and the ankle marker in relation to the ground (Figure 5).

- Knee flexion maximum [°]
  Lowest knee angle value during the whole touchdown and takeoff phase (Figure 6).

- Take off angle [°]
  Angle between the resultant velocity vector made relative to the ground (Figure 7).

Figure 4. Illustration of knee angle at touchdown.

Figure 5. Illustration of leg angle at touchdown.

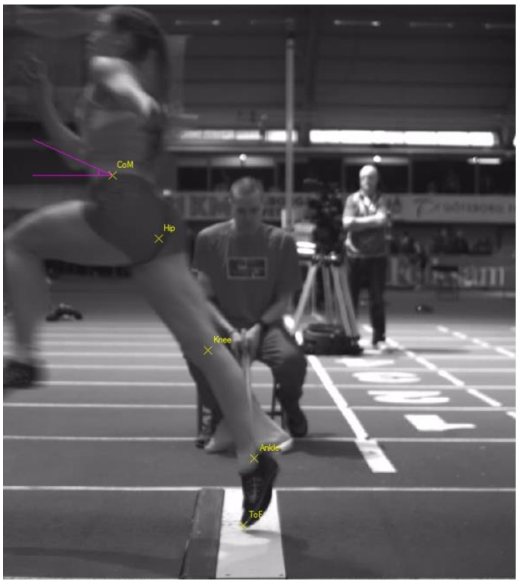

Figure 6. Illustration of knee flexion maximum.

Figure 7. Illustration of take-off angle.

Definition of categories

Four categories of variables were defined; speed, accuracy, strength and technique. The speed category was defined as variables related to velocity. Accuracy was defined as variables related to hitting the jumping board. Strength was defined as variables related to resisting and producing muscle force and technique variables was defined as the remaining variables related to the ability to perform a task/skill.

Analysis of data

Matlab (Matlab®, Version 8.5.0.197613 (R2015a), The MathWorks, Inc.) was used to calculate the above mentioned variables from data created in QVA. The computed variables were then statistically analyzed in JMP 11(JMP®, Version 11.0.0. SAS Institute Inc.). Statistical test was chosen based of Djurfeldt, Larsson & Stjärnhagen (2010) and Bryman & Nilsson (2011).

Correlation

All data parameters were evaluated regarding normality with the Shapiro–Wilks test recommended by Ghasemi & Zahediasl (2012) before tested for significant correlations and predictions. For normally distributed variables Pearson's product moment correlation was used for testing correlation with jump distance, with an with an α-level set at $p<0,05$ for the whole study. For non-normally distributed variables Spearman's ρ was used. Relationship strength was defined based on recommendations made by Portney & Watkins (1993) published in Reiman & Manske (2009). A weak relationship was defined as an r value between 0.25-0,5, moderate-good between 0,5-0,75 and good to excellent correlation above 0,75.

Bivariate linear regression analysis

Bivariate linear regression analysis was used for testing variables prediction with jump distance, with residuals analyzed for normal distribution. The coefficient of determination (R^2) was used to judge prediction strength between variables.

Multiple regression analysis

Stepwise regression analysis using forward selection and analysis of residuals regarding relationship with other variables was used to create a multiple regression model. Based on the residuals produced by the prediction of run up speed and official jump distance a comparison was made with the other 17 key variables in order to seek out possible left out relationships. Previously suggested theoretical models by Graham-smith et al. (2005) (theory model 1) and Bridgett et al. (2005) (theory model 2) were analyzed using multiple linear regression.

Ethical considerations

According to Bryman & Nilsson (2011) there are four different kinds of principles when it comes to basic methodological ethics. These four principles are regarded as information, consent, confidentiality and usage. In this study the participants were not informed about the recording of their jumps as mentioned above and to our knowledge did not sign any agreement regarding participation. However in order to not affect the athletes' performance during the competition some discretion was necessary and the officials and involved federations were all informed of the measurement. The competition in itself is also a public event and all the results are publicly available data. The film sequences were also exclusively used for this study and were handled with confidentiality. A case could be made regarding some of the participants in this study have been published with clear pictures. However no athlete is mentioned by name and no personal information was present in this study. In the end one cannot guarantee that all involved athletes agreed to be studied; however all involved federations approved and wanted this measurement done. In order to make sure all principles of ethics are achieved the involved athletes' should either have been contacted in advance or after the measurement in order to assure the principles of information and consent to be fulfilled.

Results

A total of 33 jumps (n=33) were analyzed with jumping distances ranged from 5.25-6.21 m and a mean of 5.77m (+-0.23). The mean, standard deviation and ranges of basic data and key variables are shown in table 1. For this study the mean horizontal take-off velocity was 8.32 m/s (+-0.65m/s) and mean vertical take-off velocity was 2.73 m/s (+-0.66 m/s). The resultant velocity at touchdown was slower compared to take-off velocity with values of 8.48 m/s and 8,79 m/s respectively. This also results in a net positive mechanical energy at 0,29 m/s. The mean loss in horizontal velocity was also only -0,16 m/s compared to previously reported values around -1.5 m/s, however the gain in vertical velocity appears to be normal at 2.8 m/s.

Table 1. Mean values, standard deviation and ranges for basic data**.**

	Mean (n=33)	SD+/-	Range		Mean (n=33)	SD+/-	Range
Official jump distance	5,77 m	0,24 m	5,25-6,21 m	Δ Horizontal velocity	-0,16 m/s	0,8 m/s	-1,62-1,89 m/s
Total jump distance	5,85m	0,22 m	5,41-6,25 m	Δ Vertical velocity	2,8 m/s	0,8 m/s	1,46-4,2 m/s
Contact time	128 ms	9,44 ms	110-145 ms	Take-off angle	18,22°	4,6°	10,91-28,12°
Horizontal velocity TD.	8,48 m/s	0,9 m/s	5,86-9,82 m/s	Knee angle TD	158,24°	4,8°	150,4-173,5°
Vertical velocity TD.	-0,07 m/s	0,44 m/s	-1,1-1,02 m/s	Leg angle TD	70,26°	3,18°	64,1-74,9°
Horizontal velocity TO.	8,32 m/s	0,65 m/s	6,68-9,73 m/s	Knee flexion max	23,5°	5,3°	13,8-35,9°
Vertical velocity TO.	2,73 m/s	0,66 m/s	1,52-3,91 m/s	C.O.M td	94,5 cm	4,5 cm	85,1-103 cm
Resultant velocity TD.	8,49 m/s	0,9 m/s	5,87-9,82 m/s	C.O.M to	116 cm	5,7 cm	104-125 cm
Resultant velocity TO.	8,79 m/s	0,6 m/s	7,49-9,97 m/s	ΔC.O.M	21 cm	3 cm	16-29 cm
ΔResultant velocity (mechanical energy)	0,29 m/s	0,73 m/s	-0,89-2,13 m/s	Toe-board distance	7.9cm	5,6 cm	0,5-19,7cm

i. Relationship between key variables and jump distance

All correlations are shown in figure 8. Resultant velocity at touchdown (run up speed) had the highest correlation with official distance with a correlation of r =0.63 (p<0.0001). Horizontal velocity at touchdown also produced a moderate correlation with official distance with a correlation of r=0.63 (p<0.0001). For vertical velocity at touchdown, vertical and horizontal velocity at take-off and resultant take-off velocity the correlation was non-significant.

Regarding mechanical energy a moderate correlation of r= -0,60 (p<0.001) was found. Even though the mean mechanical energy was positive for this group of athletes, a relationship between a longer jump distance with a negative mechanical energy is present. Related to mechanical energy is the difference in horizontal and vertical velocity between touchdown-take-off. For change in horizontal velocity and official jump distance a correlation of r= -0,62 (p<0,0001) was found and change in vertical velocity produced a correlation of r=0,35 (P<0,05). In essence a bigger reduction in horizontal velocity was moderately related to a longer official jump distance.

Toe-board distance, Take-off angle, Leg angle and knee angle all produced non-significant correlations. However knee flexion maximum produced a correlation of r= -0.40 (p<0.05). For the centre of mass variables only difference in relative height produced a significant correlation with official distance, r=0,39 (p<0,05). Contact time produced a correlation of r= -0,38 (p<0,05).

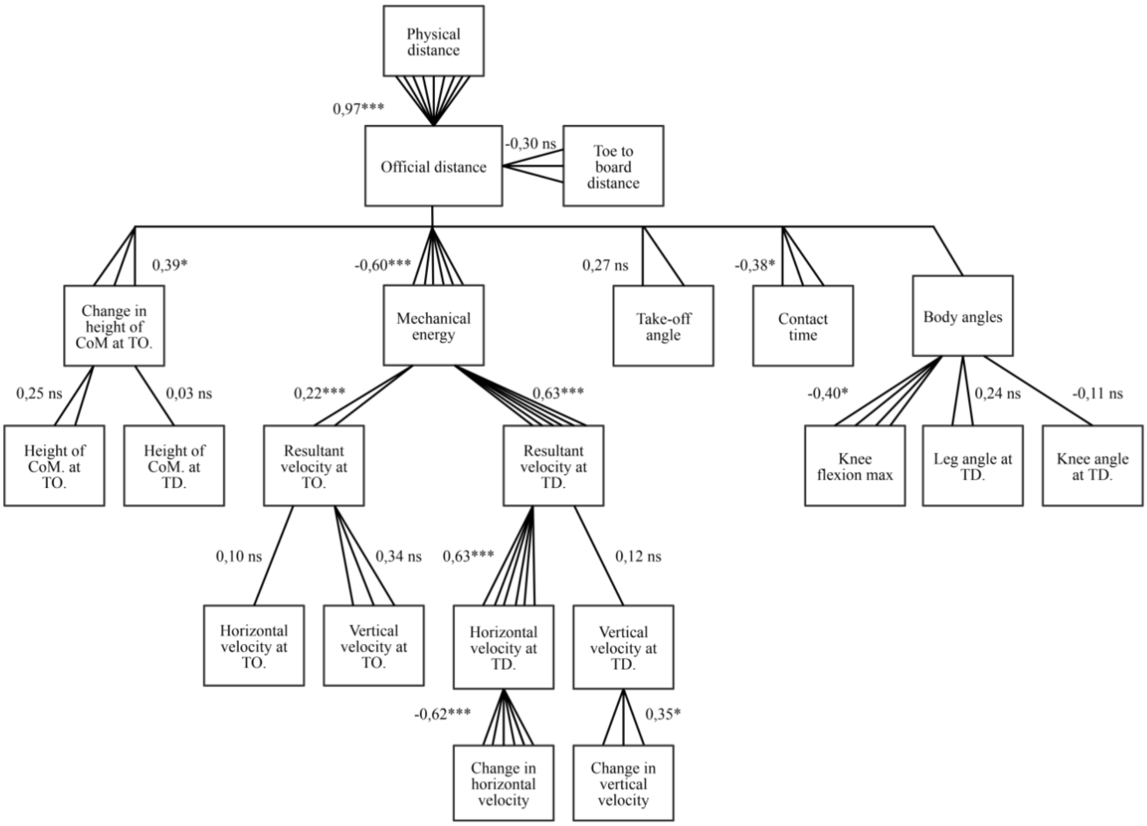

Figure 2. Correlations between key variables and official jumping distance. Each line indicate a coefficient of 0,1. p<0.05 * p<0, 01 **, p<0,001-0, 0001 ***.

ii. Prediction of jump distance

A summary of the regression analysis is shown in table 3. 9 of the chosen 18 key variables made significant predictions of official jump distance, where 5of these 9 variables were related to velocity. Resultant and horizontal velocity at touchdown, change in horizontal velocity and change in resultant velocity stood out compared to the rest, producing significant coefficients of determination between 35-40%. Knee flexion maximum, height change in centre of mass, contact time and vertical velocity all produced significant predictions although each variable only explained between 12-16% of the variance in official distance. Toe-board distance was also able to significantly predict official jump distance by explaining 20% in variance.

Table 2. Linear regression values and predictions of official distance.

	R^2	SE	F	P		R^2	SE	F	P
Resultant velocity TD	39,5%	0,036	20,3	<0,0001	Vertical velocity TO.	11,50%	0,06	4	ns
Horizontal velocity TD.	39,3%	0,036	20,0	<0,0001	Knee angle TD.	10%	0,008	3,45	ns
Δ Horizontal velocity	37,9%	0,041	18,9	<0,0001	Takeoff angle	7%	0,009	2,39	ns
Δ Resultant velocity	35,8%	0,047	17,3	<0,0001	C.o.M TO.	6,40%	0,72	2,1	ns
Toe-board distance	20,3%	0,68	7,9	<0,01	Leg angle	5,70%	0,013	1,9	ns
Knee flexion max	16,2%	0,007	5,99	<0,05	Resultant velocity TO.	4,90%	0,069	1,6	ns
Δ C.o.M	15,3%	1,18	5,62	<0,05	Vertical velocity TD.	1,50%	0,095	0,47	ns
Contact time	14,4%	0,0004	5,21	<0,05	Horizontal velocity TO.	1,10%	0,065	0,32	ns
Δ Vertical velocity	12,20%	0,05	4,4	<0,05	C.o.M TD.	0,00%	0,93	0,02	ns

iii. Multiple regression analysis and predictions of jump distance

Toe to board distance showed a significant correlation with residuals and was the first variable included in a multiple regression analysis (Figure 9). Run up speed produced a coefficient of determination of R^2=0,395 (p<0,0001), adj. R^2 =0,38 on its own and with the inclusion of toe-board distance the prediction increased to adj.R^2= 0,48 (p<0,0001) (Figure 10).

Prediction formula for model 1:
4,63 + (0,148 * Resultant velocity T.D) + (-1,485 * Toe-board distance)

The next variable included in the multiple regression was ΔC.o.M or change in centre of mass height, which was related with the residuals by R^2=0,15 (p<0,05). The inclusion of ΔC.o.M increased the coefficient of determination to adj. R^2= 0,55 (p<0,0001) resulting in an increase of 7% in predicting capacity for the model.

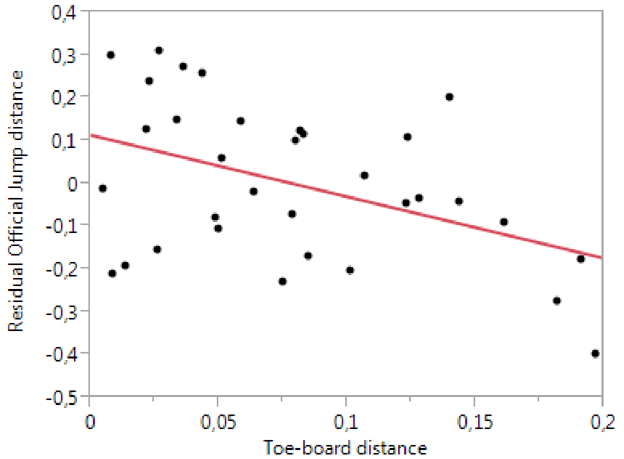

Figure 4. Toe-board distance and residual relationship. R^2=0,19 (p<0,05).

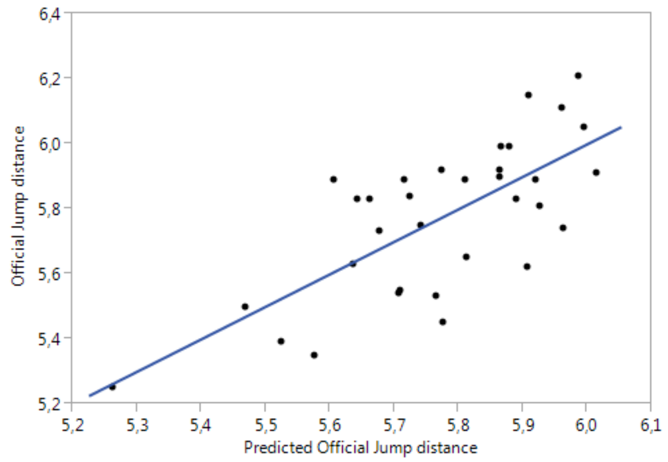

Figure 3. Multiple regression model 1 for toe-board distance and run up speed. R^2 adjusted = 0,48, (p<0,0001).

Prediction formula for the model 2:

4,26 + (-1,33 * Toe-board distance) + (0,14* Resultant velocity TD.) + (1,98* ΔC.o.M)

No other significant correlation was found between residuals and the remaining 15 key variables. As an additional control a stepwise regression was made. This stepwise regression also resulted in the variables of resultant velocity TD, Toe-board distance and ΔC.o.M was chosen as the best variables for a multiple regression analysis. For this group of athletes the conclusion was made that no other variable would improve the prediction without creating an artificial improvement in predicting capability. The regression model can be seen in figure 11.

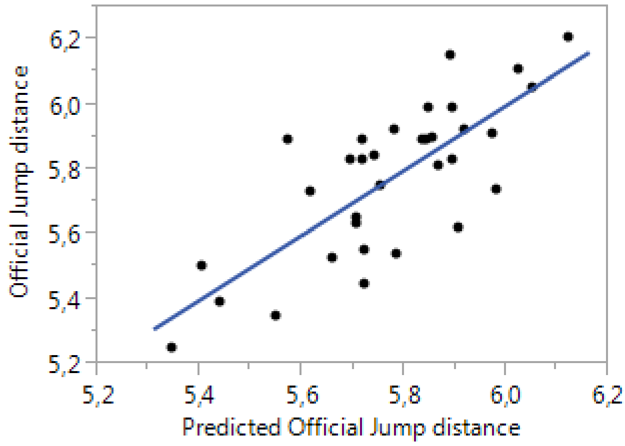

Figure 5. Multiple regression model 2 with toe-board distance, resultant velocity TD and ΔC.o.M. Adj.R^2= 0,55 ($p<0,0001$).

Theory model 1 consisting of resultant velocity TD, leg angle and knee angle at TD produced a coefficient of determination of adj. R^2=0,36 ($p<0,01$) which is a decrease in predicting capability compared with run up speed on its own (R^2=0,395 ($p<0,0001$), adj. R^2 =0,38). Knee angle and leg angle did not significantly add to the prediction and as a result the adjusted R^2 is lower for this model. This can also be seen in the formula for the prediction where the influence of knee angle and leg angles is almost nonexistent.

Prediction formula Theory model 1:

5,55 + (-0,007 * Knee angle) + (0,0014 * Leg angle) + (0,15 * Resultant velocity)

Theory model 2 consisting of resultant velocity TD, Δresultant velocity and ΔC.o.M however resulted in an increase in predicting capability compared to run up speed alone with an adj, R^2 = 0,47 ($p<0,0001$). However the predicting capability of Δresultant velocity was non-significant in the model and once again this can be seen in the formula by its small influence on the end result.

Prediction formula Theory model 2:

4,43 + (0,16 * Resultant velocity TD) + (-0,08 * Δresultant velocity) + (2,17 * ΔC.o.M)

Discussion

Results discussion

Linthorne (2008) states that the best women long jumpers reach distances of about 6.5-7.5m. If the definition of an elite athlete is drawn at 6.5m then the athletes in this study do not reach an elite level performance wise and are below the international standards with the best jump reaching 6.21m. The relatively large standard deviation of 0.9 m/s and range of 5,86-9,82 is also an indication of that the spread between athletes is quite large in this group. The level of the competition is on the other hand at the highest domestic level and in that regard the athletes reach elite status on a national level. As a consequence it is also not possible to be certain that the techniques displayed here are representable for real elite women long jumpers. There is however a possibility to determine important factors influencing the long jump within this group and to analyze the technique the best Swedish athletes displays.

The majority of the basic data gathered in this study are in agreement with previously reported values by Graham-smith et al. (2005); Hay et al. (1986); Seyfarth et al. (2000) and the typical values of women elite jumpers from Linthorne (2008). A table comparing the results from this study with previous results is available in the appendix (Appendix 2.) Reports on contact time for women jumpers are scarce, however the mean contact times reported appears to be plausible. Values reported for take-off angle, knee angle, leg angle, knee flexion max, Centre of mass height and height changes are all within limits. A slightly lower horizontal velocity at touchdown can be seen in our data with a mean of 8.48 m/s compared to the typical value of 9.5 m/s suggested by Linthorne (2008) for elite women athletes

A clear conclusion can be made that run up speed and horizontal velocity at touchdown are the most important variables in predicting jump distance and the most influential variable for a successful long jump performance, which has been widely reported by other studies. Hay (1993) reports correlation coefficients in the ranges of 0,7-0,9 for official jumping distance and horizontal velocity at touchdown and while our correlation does not quite reach that level it is close at $r=0,63$ ($p<0.0001$).

Hay et al. (1986) reported a significant relationship between effective flight distance and speed of take-off ($r=0.83$), horizontal velocity at take-off ($r=0.77$) and vertical velocity at take-off ($r=0.4$). These correlations were not found in this study and the results from our correlation analysis are more in line with reports from Graham-smith et al. (2005) who reported no correlation between vertical, horizontal or resultant speed at take-off and official distance. However Graham-smith et al. (2005) found no correlation between run up speed and flight distance, $r=0,496$, ($p>0.05$) and our results differ in that regard. A possible reason why is because the standard deviation and range are much larger in our study with ranges of 5,87-9,82 m/s compared to Graham-smith et al. (2005) values of 9.34-10,57 m/s which indicate a more homogenous group. Graham-smith et al. (2005) also touches on the subject that a high signal to noise ratio can be hard to get in a homogenous group and if the skill level of the athletes in this study was more equal the signal would probably become less clear. The importance of individual technique variables probably increases when the ranges and spread of run up speed decreases in a more homogenous group and as a result run up speed becomes less influential.

An interesting finding related to the skill level of the athletes is the fact that this group of athletes had a mean gain in mechanical energy of 0.29 m/s. A gain in mechanical energy could be seen as positive at first glance however studies by Bridgett et al. (2006) and Seyfarth et al. (2000) suggests that a net loss is necessary in order for optimal performance. In the study by Bridgett et al. (2006) the athlete jump had a net gain in mechanical energy only for speeds below 8 m/s and for higher speeds a net loss in mechanical energy was required. For speeds below 8m/s a gain in mechanical energy is possible and by looking at the mean resultant velocity at TD for the whole group the velocity (8.49 m/s) a mean gain in mechanical energy seems plausible. However a negative mechanical energy and breaking of horizontal velocity was also related to a longer jump distance with correlations of $r= -0,60$ ($p<0.001$) and $r= -0,62$ ($p<0,0001$) respectively. Even though a maximum retention of mechanical energy is to strive for it appears as if mechanical energy could be seen as an indication of the skill level of the athletes where a gain in mechanical energy is sub-optimal.

For predicting jump distance 5 velocity variables, two technique variables, one strength and one accuracy variable was identified as significant prediction variables. The four velocity variables of run up speed, horizontal velocity TD, Mechanical energy and change in horizontal velocity were the most important variables who could individually explain the most of the predicted jump distance on their own. Strength, accuracy and technique appeared not to be as important as speed, although they made significant predictions and influence the final jump distance. A lesser flexion of the knee (greater strength), shorter toe-board distance (better accuracy), bigger change in centre of mass height (technique related to horizontal and vertical velocity gain) and a shorter contact time were all significantly related to a longer jump distance in various degrees. As a final statement the single most important variable for this group of athletes was run up speed, predicting 39,5% of the jump distance.

The final trial of multiple regression models resulted in the variables of ΔC.o.M, toe-board distance and resultant velocity TD were selected as the best model based of a stepwise and residual analysis. This model could explain 55% of the variance in predicted jump distance for this group of athletes. A quick interpretation of the formula for the model indicates that a higher resultant velocity, a lower toe-board distance (shorter distance to board = better accuracy) and a greater gain in centre of mass height is beneficial for a longer jump distance.

Stepwise regression has its drawbacks regarding choosing of a true model and this model might only hold true for this group of athletes; as a result a model based on theory was also used. The theory induced models by Graham-smith et al. (2005) and Bridgett et al. (2006) both resulted in significant models but the individual significance of each variable included varied within the model. A clear interrelation between variables could also be seen where some variables explain the same thing. The stepwise regression clearly illustrated this when one variable could be significant if included in the first step but non-significant if a related variable was included; for example horizontal velocity TD became non-significant when resultant velocity TD was added. This could be the reason for the individually poor significance levels on the three theory induced models, even though the model as a whole is significant. It is up to the beholder to decide if a significant theory induced model is viable even though individual variables within the model are not significant.

Method discussion

A use of a multiple camera system was not viable due to environment limitations, however a high speed camera operating at 200 Hz provides a technical advantage compared to current and older studies. Regarding research methods 2-d kinematics is the most common way of capturing the long jump, often with cameras operating at 100 or 50 Hz. A higher operating frequency (present in this study) could potentially provide more accurate data for capturing the very short time frame of the touchdown and take-off phase.

The competition and video capturing of the jumps took place in 2014 and as a consequence there is a possibility for data being lost on the way. By not being present during the jumps we cannot be sure whether a disallowed jump was due to injury or overshooting of the board. Neither can we be sure whether an athlete was performing a “safe jump” in order to get a result on the board. This could affect the end results since some athletes had very few jumps and a “safe jump” could force the athlete to use a different jumping technique.

Another potential issue arose regarding the reliability of marker placement during the digitizing of the videos since a substantial reliability trial was not an option. An optimal reliability test would be to follow Graham-smith et al. (2005) who digitized each jump 3 times and took the average value of these three jumps in order to reduce errors. The athletes also wore different kinds of clothes, some looser fitting than others, which further complicated the placement of the markers. This is however a known issue which Graham-smith et al. (2005) touches upon, and as a consequence difficult marker placements were carefully discussed and revised to reduce possible errors.

For the statistical tests careful consideration was taken in order to not artificially induce results or manipulate the data. All variables were analyzed regarding normality with a Shapiro-Wilks test in order to select the correct tests. Validity of the statistical tests was secured by having theory behind the inclusion of every variable and only variables related to long jumping technique was chosen based of previous studies. As a consequence all the data, except toe-board distance, can be validated with regards to previous reports as shown in table 1. Toe-board distance is however discussed as an accuracy variable and although no normalized data is included the data was validated based of Hay et al. (1986) and Hay (1993).

Conclusions

The findings of this study conclude that a fast run up speed and horizontal velocity at touchdown are the most important variables for a successful long jump. A net loss in mechanical energy as well as a breaking of horizontal velocity during the jump phase is also strongly related to a longer jump distance. By including one variable from each of the categories of speed, accuracy and technique in a multiple regression analysis an even better prediction could be made on official jump distance. For the whole group 55% of the jump distance could be explained by this model, compared to 39.5% for run up speed alone; suggesting a complex relationship between jumping technique and long jump performance.

Practical implications

Further studies or a practical implication could be to test the sprinting capabilities of the athletes to determine if the athlete has the capability to run faster in competition by measuring maximum sprints and comparing competition or training run up speeds. This could be a useful indication if the athlete has a psychological limitation to a better performance in the long jump. Using mechanical energy as a measure of optimal performance could also be useful, where a reduction in mechanical energy and breaking during the jump appears to lead to optimal performance. Based on this theory the athlete should not gain velocity during the jump phase but rather convert run up speed into take of speed, while preserving as much energy as possible. Further studies validating the necessity of a negative mechanical energy as a performance measurement could be useful. Additionally studies looking at individual athletes or more homogenous groups of elite athlete using multiple regression analysis could be useful to better determine the interrelationship between variables predicting long jump performance.

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Appendix

A table which explains abbreviations and the terminology in subject
Touchdown = The first clear frame where the jumper touches ground.
Take-off = The first clear frame where the jumper leaves contact with the ground.

TD = Touchdown.
TO = Take-off.
Run up = The entire running phase in the long jump.
Toe to board distance = Distance between tip of foot and board at touchdown.

Leg angle = The angle between the knee and ankle marker in relation to the ground.
Knee angle = The angle comprised by the hip, knee and ankle markers.
Ankle angle = The angle comprised by the knee, ankle and tip of foot markers.
Angle of attack = The leg angle at touchdown.
Take-off angle = The angle at which the center of mass is directed at take-off.
Mechanical energy = Change in resultant velocity between touchdown and take-off. A positive mechanical energy equals an increase in resultant velocity between TD. and TO.
ΔResultant velocity = Mechanical energy.

Physical distance = Official distance + Toe to board distance, the total length of the jump.
Official distance = The competitive length of the jump.
Contact time = The total amount of time the athlete has contact with the ground during touchdown and take-off.

Resultant velocity = Horizontal and vertical velocity combined.
Run up speed = Resultant velocity.

Δ (delta) = Used to describe change. For example "Δ vertical velocity" indicates a change in velocity.

R^2 = Coefficient of determination.
SE = Standard error.
F = F-test value.
P = Probability.

Marker setup definition and explanation.
CoM = Centre of mass. Located at 55-60% of the jumpers total height.
Hip = Greater trochanter.
Knee = Femoral condyles.
Ankle = Lateral malleolus of fibula.
ToF = Tip of foot. Located at the most anterior part of the toes.

Appendix 2. Comparison between basic data and previous studies

			Linthorne (2008)	Graham-smith et al. (2005)		Hay et al. (1986)		Seyfarth et al. (2000)	Bridgett et al. (2006)	
	Mean (n=33)	Sd +/-	Suggsted typical values (women)	Mean	Sd +/-	Mean	Sd +/-	Reported values	Mean	Sd +/-
Official jump distance	5,77 m	0,24 m	6,8 m							
Total jump distance	5,85m	0,22 m								
Contact time	128 ms	9,44 ms	110 ms						127 ms	+-11 ms
Horizontal velocity TD.	8,48 m/s	0,9 m/s	9,5 m/s	9,93 m/s	0,37 m/s	10,4 m/s	0,44 m/s			
Vertical velocity TD.	-0,07 m/s	0,44 m/s	-0,1 m/s	-0,18	0,21 m/s	0,2 m/s	0,18 m/s			
Horizontal velocity TO.	8,32 m/s	0,65 m/s	8.0 m/s	8,55 m/s	0,35 m/s	8,9 m/s	0,44 m/s			
Vertical velocity TO.	2,73 m/s	0,66 m/s	3.1 m/s	3,37 m/s	0,32 m/s	3,2 m/s	0,27m/s			
Resultant velocity TD.	8,49 m/s	0,9 m/s		9,94 m/s	0,37 m/s	10,4 m/s [4]	-			
Resultant velocity TO.	8,79 m/s	0,6 m/s	8,6 m/s	9,20 m/s	0,25 m/s	9,46 m/s [4]	-			
ΔResultant velocity (mechanical energy)	0,29 m/s	0,73 m/s		-0,74 m/s	0,23 m/s	-0,94 m/s [4]	-	Net loss [2]	Net loss of 10% [3]	
Δ Horizontal velocity	-0,16 m/s	0,8 m/s	-1,5 m/s	-1,38 m/s	0,26 m/s	-1,5 m/s [4]	-			
Δ Vertical velocity	2,8 m/s	0,8 m/s	3,2 m/s	3,54 m/s	0,23 m/s	3 m/s [4]	-			
Take-off angle	18,22°	4,6°	21 °			20,2°	1,8°	10-20° [1]		
Knee angle TD	158,24°	4,8°	161 °	167 °	4,7 °					
Leg angle TD	70,26°	3,18°	63 °					65-70° [1]		
Knee flexion max	23,5°	5,3°		26,5°	5,2°					
C.O.M td	94,5 cm	4,5 cm	96 cm	98 cm	4 cm					
C.O.M to	116 cm	5,7 cm	120 cm	127 cm	4 cm					
ΔC.O.M	21 cm	3 cm	24 cm	29 cm	3 cm					
Toe-board distance	7.9cm	5,6 cm								

1. Suggested optimum angle
2. Net loss for speeds higher than 5 m/s (for optimal performance)
3. Net loss for speed higher than 8 m/s
4. Calculated with vertical and horizontal mean values

Table of figures