



Biomechanical Effects of Flamenco Footwork

by

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Footwork is one of the basic features of flamenco dancing and is performed in traditional high-heeled shoes. The purpose of this study was to analyse the mechanical profile of flamenco dancing in terms of vertical ground reaction force, and knee joint kinematics of the supporting limb in footwork technique in order to understand causes which predispose injuries derived from the practice of flamenco dancing. The participant in our study was a professional female flamenco dancer (34 years, 58 kg, 1.65 m) who performed the ZAP 3 test, a sequence of single strikes of the feet performed continuously for 15 s. 3D lower extremity kinematic data were collected using a five-camera motion analysis system (Vicon; Oxford Metrics Ltd., Oxford, UK). Ground reaction forces were recorded using a Kistler force plate. Our analysis was based on 30 cycles of each lower limb consisting of 177 footwork steps. The vertical component of the ground reaction force did not reveal any significant differences between the left and the right limb. The most dynamic strike was provided by the heel (twice the participant's body weight). The mean angular displacement of the supporting limb's knee was $\sim 27^\circ$. Results reveal that these impacts could make the knee joint more prone to injuries.

Key words: kinematics, ground reaction force, knee flexion, injury.

Introduction

Flamenco, a highly emotional and sensitive dance, is one of the most emblematic features of Spanish culture. It is both physically and mentally demanding, with an emphasis on technical footwork execution and aesthetic arm and trunk movements (Vargas, 2006). Years of training are necessary to achieve the level of proficiency held by professional flamenco dancers (Pedersen et al., 1999).

Footwork steps (*zapateado*) form one of the basic components of flamenco dancing and are performed in traditional high-heeled shoes, 6 to 7 cm for women. The mean frequency of tapping is 4 steps per second. Dancers usually reach

frequencies of up to 12 steps per second (Vargas, 2006). The percussive footwork and vibration patterns created during dancing impose huge demands on the musculoskeletal system (Bejjani et al., 1988). Additionally, the dancer must also strike the ground according to a specific rhythmic pattern inherent to flamenco music (Vargas, 2006).

Therefore, proper execution of movements minimises the risk of injury accompanying foot-ground contact as reported by several studies (Bejjani et al., 1988; Pedersen and Wilmerding, 1998; Vargas, 2006; Gorwa et al., 2019a). One of the parts of the dancer's body which suffers the most is the knee joint (Bejjani et al., 1988; Castillo-López et al., 2016; Echegoyen et al., 2010; Pedersen and Wilmerding, 1998). To our

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knowledge there are no studies which consider the effect of the dynamic footwork on the knee joint kinematics during flamenco dance technique. Since some authors reported that lower-skilled athletes had a twofold increase in incidence of all severe injuries as a group compared to higher skill level groups (Chomiak et al., 2000), our case study analysis is based on data from a highly advanced flamenco dancer.

Shock waves generated during dancing are propagated along the human musculoskeletal system, becoming one of the main reasons for joint degeneration (Gorwa et al., 2019b). When dancers strike the ground, they subject structures of the supporting limb (joints, muscles, tendons, ligaments) to serious loads due to high peaks of force which are several times their body weight (Echegoyen et al., 2013; Gorwa et al., 2019b). A key component in reducing vertical ground reaction force (GRF) is damping and this is performed with the legs. The knee appears to be the main modulator of leg stiffness, as the lever arm lengths of the femur and tibia place the knee in the best position of all the lower extremity joints to help attenuate the vertical GRF (Gorwa et al., 2019a, 2019b). There are several studies researching the level of GRF in percussive dances (Echegoyen et al., 2013; Klopp, 2017; Mayers et al., 2010), but only one study has focused on GRF in the flamenco dance (Echegoyen et al., 2013). We found only a few investigations where a knee joint angular displacement into flexion has been reported both in student and professional flamenco dancers, as a result of ergonomic adaptation in flamenco dancing and identified its magnitude (Echegoyen et al., 2013; Forczek and Vargas-Macías, 2015; Pedersen and Wilmerding, 1998). Considering the functional task of the lower limbs during *zapateado*, one limb is recognised as being the supporting leg, while the other is a non-supporting one. The results revealed that knee flexion of the supporting leg during footwork is between 10 and 15° (Echegoyen et al., 2013) and 35.3±8.2° (Forczek and Vargas-Macías, 2015).

Flamenco can also introduce a risk of injury due to its athletic nature. Despite the growing number of studies on flamenco dancing, there is a lack of research focused on understanding how dance technique can affect the dancer's body and how this style of dance can cause specific injuries. Therefore, the purpose of

this study was to analyse the effect of the vertical component of the ground reaction force on knee joint kinematics of the supporting limb in footwork technique in order to understand causes which predispose injuries and to provide some recommendations to flamenco practitioners. The secondary aim was to optimize the protocol applied in order to be used efficiently in a larger population.

Methods

Participant

Our study was based on a biomechanical registration of *zapateado*, the most typical combination of footwork steps, used in flamenco choreography. Thirty cycles performed continuously for 15 s by lower limbs were analysed. Each cycle composed of a sequence of 6 footwork steps was performed by a professional female flamenco dancer: 34 years old, 58 kg, 1.65 m, 18.59% of body fat content. She had been dancing flamenco for 31 years including 16 years as a professional, with a weekly frequency of 22 hours. According to the Sobrino and Guillén (2017) scale for professional dancer experience, our participant could be considered a senior professional, the highest level. Most dance studies are based on students because participation in experimental sessions requires time which professional dancers usually cannot offer (Krasnow and Kabbani, 1999). In addition, research requires an extra effort from dancers which can negatively affect their shows.

The participant did not report any musculoskeletal or sub-acute injury within 12 months prior to the study, nor were any surgical interventions reported by the participant.

She gave written consent to participate in the study and the experimental protocol received approval from the Ethics Committee of the San Antonio Catholic University of Murcia (Spain); the trial was registered at www.clinicaltrials.gov (NCT04166708).

Measures

One of the strengths of this research is that a real choreographic sequence was studied with practical implications to professional performance. The main task of the participant was to perform the ZAP 3 test (Vargas, 2006), i.e., a sequence of 6 footwork steps (Figure 1) which is performed twice: once with the right foot and

once with the left. It includes tapping with the ball of the foot, heel and the tip of the toe for 15 s (the duration of the test). The dancer intends to create the loudest possible sound, perform the steps as quickly as possible and maintain the rhythm. The test was performed using specific high-heeled shoes (0.06 m tall) and was carried out twice: 1. when the right foot (the dominant one) was on a force plate; and 2. when the left foot (non-dominant) was placed on a force plate.

According to this protocol, BF, HD1, HD2 and HD3 footwork steps were determined as performed by the supporting limb, while HT and TT by the non-supporting limb.

Design and Procedures

The footwork test was carried out in the Biomechanics Laboratory at the university. Three-dimensional lower extremity kinematic data were collected using a five-camera motion analysis system at a sampling rate of 120 Hz (Vicon; Oxford Metrics Ltd., Oxford, UK). Body segments were defined according to the Golem model and 35 reflective markers were attached to the head (4), trunk (4), pelvis (3), arms (7) and legs (5). GRF was recorded using the Kistler force plate at a sampling rate of 1000 Hz. From the collected data, we identified kinematic variables describing the temporal and phasic structure of footwork, as well as the knee joint angular changes in the sagittal plane. At the same time, the vertical component of GRF was measured using the force plate. The synchronization of the optoelectronic system and the force plate signals was performed with the Workstation software implemented in the Vicon system.

The participant was asked to perform the test twice, in order to place both the right and the left foot on the force plate while performing the steps. Prior to the test we identified the right leg as dominant for the dancer (Elias and Bryden, 1998).

Afterwards, the knee strength capacity was measured as isometric flexion and extension torque using dynamometric measurements (Hottinger V9B force transmitter) in line with the generally accepted methodology (Buśko and Staniak, 2007).

Statistical analysis

IBM SPSS Statistics 22 software was used for statistical analysis. Descriptive statistics were calculated for average values, standard deviation

(SD), minimum and maximum. The conducted analyses adopted the following level of significance $p < 0.05$. The normality of distribution of the variables was verified using the Shapiro-Wilk test. The t-student and Wilcoxon tests were used to determine the dependence of variables in performances 1 and 2 and between the supporting and the non-supporting limb. The Kruskal-Wallis test was used to relate the variables with the different footwork steps. Correlation analysis was carried out to study the relationship among variables.

Results

Altogether, our dancer carried out 177 footwork steps in each performance, which constituted 30 cycles with both lower limbs. During the measurement sessions, the dancer achieved a mean frequency of 11.8 footwork steps/s. Descriptive results are showed in Table 1.

GRF analysis did not reveal any significant differences in terms of the mean values between the left and the right limb ($p = 0.316$), however, on the basis of dynamometric results we identified the right knee as stronger, which confirmed the questionnaire's result. The registered values of the extensors / flexors torque were respectively: 116/ 76 [Nm] for the right knee, and 93 / 54 [Nm] for the left knee. Statistically significant differences were found between GRF values for the supporting and the non-supporting limb during the test ($p < 0.05$). We observed a very regular, repetitive and homogeneous performance of the same steps throughout the test.

Figure 2 illustrates the mean values of GRF, expressed as Body Weight percentage (% BW), accompanying each footwork step. Regarding vertical force, the results revealed significant differences for different steps ($p < 0.05$). This means that steps performed with different parts of the foot implied different levels of pressure to those elements.

The most dynamic strike was provided by the heel (HD1, *Tacón*) where the mean value of the vertical component of the GRF was more than twice the participant's body weight. Footwork BF, HD2, HD3 were accompanied by similar reaction force values (~1.6% BW). The lowest force value was provided by the toes (TT, *Punta*) (0.3 % BW).

Figure 3 illustrates sample knee joint angular displacement accompanying each

footwork step. The analysis revealed a significant correlation among the level of GRF and the angular knee position, yet it was moderate and negative dependence ($R = -0.5$; $p < 0.05$).

Considering the knee joint angular displacement of the supporting leg during footwork, significant differences were observed

between the results in both performances ($p < 0.05$) (Table 1).

Although the position of the knee joint of the supporting leg remained quite stable throughout the test ($\sim 27^\circ$), we could observe some slight differences during different types of footwork (Figure 4).

Table 1

Descriptive results registered for the participant during performance 1, performance 2, and for both performances (GRF – Ground Reaction Force)

	Performance 1 ●±SD (min,max)	Performance 2 ●±SD (min,max)	t-student Wilcoxon test (Performance 1 vs. Performance 2)	/ Performance 1+2 ●±SD (min,max)
GRF (% BW)	1.25±0.67 (0.14,2.69)	1.30±0.74 (0.13,2.85)	$p=0.32$	1.27±0.70 (0.13,2.85)
GRF supporting limb (% BW)	1.66±0.36 (0.86,2.69)	1.77±0.36 (1.23,2.85)	$p=0.38$	1.72±0.70 (0.86,2.85)
GRF Non supporting limb (% BW)	0.39±0.15 (0.14,0.69)	0.38±0.27 (0.13,1.70)	$t=1.86$ $p=0.07$	0.39±0.21 (0.13,1.70)
t-student / Wilcoxon test (supporting limb vs. non supporting limb)	$t=18.74$ $p<0.05$ (*)	$p<0.05$ (*)	-	$t=24.74$ $p<0.05$ (*)
Knee flexion percussive limb (°)	33.73±8.53 (24.78,53.75)	28.62±9.97 (17.14,52.10)	$p<0.05$ (*)	31.17±9.60 (17.14,53.75)
Knee flexion percussive & supporting limb (°)	29.97±4.07 (24.78,42.55)	25.07±5.22 (17.14,37.52)	$p<0.05$ (*)	27.52±5.27 (17.14,42.55)
Knee flexion percussive & non-supporting limb (°)	41.58±10.03 (29.26,53.75)	35.95±13.13 (18.79,52.18)	$p<0.05$ (*)	38.74±11.92 (18.79,53.75)
t-student / Wilcoxon test (supporting limb vs. non supporting limb)	$p<0.05$ (*)	$p=0.01$ (*)	-	$p<0.05$ (*)

*Performance 1: right foot is on the force plate; Performance 2: left foot is on the force plate;
Performance 1+2: both results. (*) $p < 0.05$*

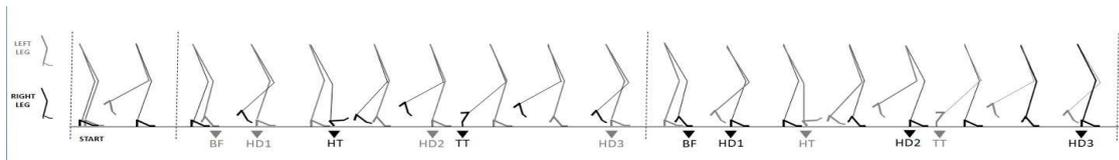


Figure 1

Sequence of the ZAP 3 footwork test (Vargas, 2006). BF (Ball of the Foot) striking only the ball of the foot on the floor; HD (Heel Drop) dropping the heel on the floor, this happens three times within the sequence between other taps; HT (Heel Tap) striking only the heel; TT (Tip of the Toe Tap) tapping the tip of the toe on the floor behind the base of support.

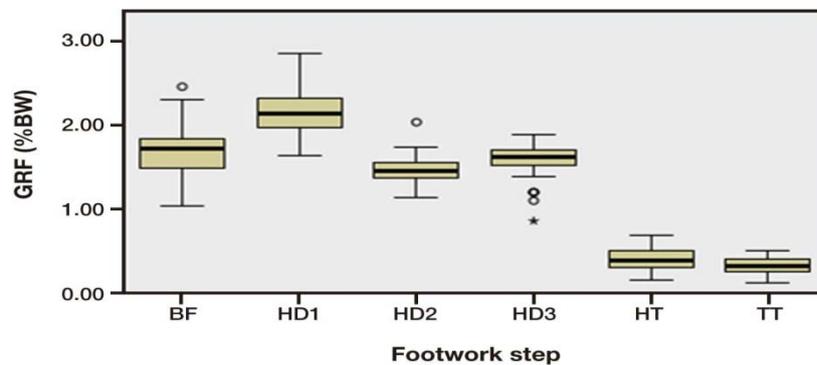


Figure 2

Ground Reaction Force (GRF) (% Body Weight, BW) recorded for each type of footwork

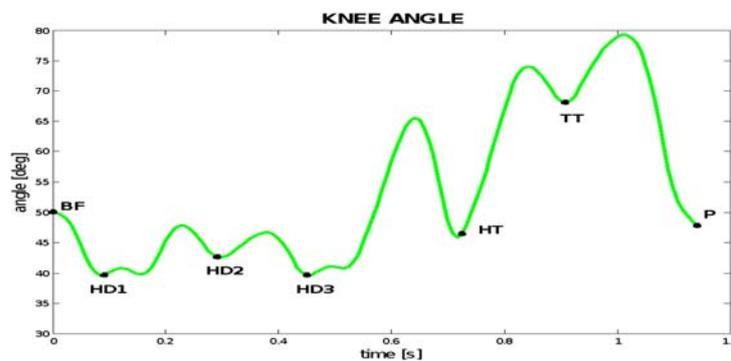


Figure 3

Sample knee angular displacements throughout the footwork test

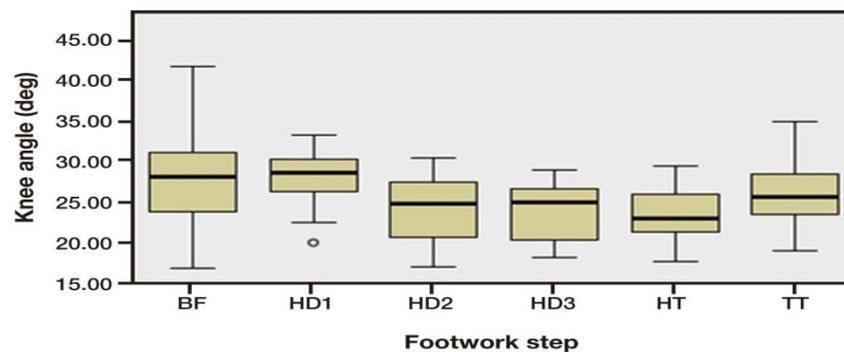


Figure 4

Knee flexion (deg) of the supporting limb during different types of footwork

Discussion

The main goal of our study was to analyse the effect of the vertical component of the ground reaction force on knee joint kinematics of the supporting limb in footwork technique. We expected that such an approach could help understand causes which predispose injuries derived from the practice of flamenco dancing and provide some recommendations to the flamenco practitioners.

Specificity of flamenco dancing

On a professional or a pre-professional training level, dancers must not only be experts in the aesthetic, stylistic, and technical aspects of dance, but also be physically capable of coping with the demands that choreography places upon them (Koutedakis and Jamurtas, 2004). Flamenco is both a highly emotional and extremely demanding dance in terms of technique. Demanding levels of exertion have been reported during professional flamenco dance performances, similar to those noted for elite athletes (Vargas, 2006). For example, the number of steps performed by professional female flamenco dancers in a ZAP-3 test should be between 159 and 176 (Vargas, 2006). Our

participant confirmed her high professional level, both physically and technically when performing 177 steps in each test, which equates to ~12 steps/s. Such a high frequency of the limb movements requires an intense activity of the muscles. It is likely that because of the overly short muscle relaxation (deactivation) time, the activity of the knee joint muscles during the footwork precludes an increase in its range of movements (Gorwa et al., 2019a).

A long list of important functions which the human musculoskeletal system has to perform includes attenuation and dissipation of the shock waves initiated with foot-ground contact. This process accompanies any human motion (Voloshin et al., 1989). One of the basic elements in flamenco dancing is the combination of steps (zapateado) aimed to create percussive sound syncopation, which occurs by striking the forefoot or heel against the ground. Flamenco dancers wear a variety of traditional shoes which do not provide adequate shock absorption (Castillo-López et al., 2016; Vargas, 2006; Vargas-Macías and Gómez-Lozano, 2008; Voloshin et al., 1989). That is why finding a natural mechanism which helps deal with body overloading during footwork is of great importance. The knee joint,

due to the spatial segment orientation of the femur and tibia, is in the best position of all lower limb joints to help attenuate the vertical GRF (Gorwa et al., 2019b).

Ground Reaction Forces

To our knowledge, only one study (Echegoyen et al., 2013) considered GRF in Flamenco dancers. While in that study, the ground response level was 0.5% of the body weight (BW), our research revealed a higher value of GRF (~1.3%BW). Strikes with different parts of the foot implied different pressure levels to those elements. Thus, the most dynamic strike was provided by the heel dropping (HD1, Tacón) where the GRF vertical component was more than twice as high as the participant's body weight. The force provided by the toes (TT, Punta) presented the lowest value (0.3%BW). We can hypothesise about reasons behind the differences recorded in these two studies. In the first case, the participants were students, while in the present study the dancer had 16 years of professional experience. Furthermore, participants in the first study performed just one type of footwork step (flat-foot): isolated steps for 5 s with no musicality or relationship with flamenco choreographies. Finally, we assume that the supporting limb in the students group was outside the force plate throughout the test, thus body weight was not used to accompany the percussion. In comparison with other percussive dances, the maximum GRF recorded in our study, 2.85 BW, is similar to that noted in tap dancing, 2.82 BW (Mayers et al., 2010), but lower than in Irish dance, 4.5 BW (Klopp, 2017). Such an important difference is understandable considering that in tap and Irish dancing, the strike is performed after leaps, hops, and jumps (Klopp, 2017; Mayers et al., 2010), like a drumstick on a drum; while in flamenco it follows the flexion and extension of knees, as if it were a hammer on an anvil. In a study by Voloshine et al. (1989), the amplitude of the heel strike-induced shock wave recorded on the tibial tuberosity was nearly three times higher for flamenco dancing than in level walking. That is why the impacts generated during footwork can trigger different types of injuries, which should be studied.

Knee joint in the dance

As Mikkelsen et al. (2018) noted, factors such as choreography and footwear create

conditions which influence the likelihood of injuries. Most professional flamenco dancers complain about knee and back injuries due to the high-heeled shoes and the nature of the percussive movements (Castillo-López et al., 2010, 2016). The redistribution of impact to the knees when dancing in heels may contribute to knee overuse syndromes such as tendinopathy or patellofemoral pain (Mikkelsen et al., 2018). Therefore, knees should be kept slightly bent to achieve a maximum amount of shock absorption (Echegoyen et al., 2013; Forczek and Vargas-Macías, 2015). It distinguishes the aesthetics of flamenco dancing (Vargas, 2006) from other percussive dances such as Irish Dance (Klopp, 2017), Mexican Folkloric Dance (Echegoyen et al., 2013) or Tap Dance (Mayers et al., 2010) where the knee joint has a more dynamic role. Furthermore, in flamenco there are no jumps which cushion the impacts, the only tilting occurs with the small swings which are achieved with the range of knee flexion movement (in our participant between 17.14 and 42.55°). If the supporting knee flexion is very small, the impact absorption would be less and would therefore generate greater overload/overuse for low back muscles (Voloshin et al., 1989). On the other hand, greater knee flexion would imply an overload in the knee joint structures (Escamilla, 2001). A proper knee position is provided by co-contraction of the hamstring and quadriceps muscles. Our results indicated that the ratio of the knee extensor and flexor torque was ~1.5, where larger absolute values were noted for the right leg. Less dynamic participation of the knees, with more maintained flexion, may produce less impact absorption through its musculotendinous system, increasing the force transmitted to the passive structures of the knee (Yu et al., 2006). Active flexion of the knee is a crucial component in impact reduction as a main modulator of leg stiffness. Knee joint angular displacement into flexion is a normal response during ground contact phases of walking, running and other gaits to allow for damping and reduction of the experienced vertical GRF (Ferris and Farley, 1997). In our study, the average knee joint values recorded for the supporting limb were similar in both sessions (~27°).

The present study has some limitation: a single participant was studied, consequently, the

results should be interpreted in a limited way. At the same time they allow to determine some relevant aspects: first, professional dancer's results revealed differences compared to the students' results (Echegoyen et al., 2013; Forczek and Vargas-Macías, 2015). Second, kinematic and dynamic results provide significant information which can optimize the technical execution of flamenco during performance on stage. Finally, the protocol applied allows to obtain useful information for injury prevention in flamenco dancers. These justify the need to carry out this type of studies on a larger sample and with an optimized protocol, which would reduce the time spent by professional participants during research work.

Conclusions

Recently, as research capabilities have progressed, the capacity to view and understand dance movements with greater clarity has emerged. While previous studies on flamenco footwork dance generally did not focus on its technical aspects, this study adds to the

knowledge on significant matters during footwork performances. Proper mechanical execution of movements (with adequate force and appropriate loudness) may not only increase flamenco skills, but also minimise the risk of injury, thus, it should be of interest to teachers. During flamenco classes and training, teachers should familiarise their students with some strategies regarding how to control the knee joint position during footwork. Future studies should involve a larger sample of participants in order to compare the forces and mechanics of all the main lower limb joints while dancing, as this could guide the development of interventions to minimise symptoms or risk of injury for flamenco dancers. Then, it seems necessary to describe the correct technical performance of the elements involved in flamenco dance to increase safety of the amateurs. It would be also interesting, in this context, to analyse how the dancer's whole body copes with dynamic footwork steps in terms of stability.

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