Journal of Dairy Research

cambridge.org/dar

Research Article

Cite this article: Tsaousioti A, Praxitelous A, Kok A, Kiossis E, Boscos C and Tsousis G (2023). Association between dam and calf measurements with overall and fetopelvic dystocia in Holstein heifers. *Journal of Dairy Research* **90**, 261–268. https://doi.org/10.1017/S0022029923000468

Received: 24 February 2023
Revised: 29 June 2023
Accepted: 3 July 2023
First published online: 17 August 2023

Keywords:
Dystocia; fetopelvic disproportion; Holstein heifers; pelvimetry

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Association between dam and calf measurements with overall and fetopelvic dystocia in Holstein heifers

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Abstract

We investigated the relationship between dam's pelvic and calf's dimensions with dystocia due to fetopelvic disproportion in the Holstein breed and estimated risk factors and dystocia probability. For this purpose, external pelvic measurements were performed in 402 heifers 15 ± 11 (1–38) days ante-partum and specific conformation measurements were obtained from their calves 1.7 ± 1.2 post-partum. Dystocia was defined as the inability of the heifer to complete parturition spontaneously within 120 min after the appearance of the amnion with normal presentation, position and posture or as having definite obstetrical obstacles within 60 min. Overall and fetopelvic disproportion dystocia incidence was 10.4% and 5.2%, respectively. Heifer measurements mainly influenced overall dystocia, whereas calf conformation was related solely with fetopelvic dystocia. Specifically, heifers with a small pelvis (hip width <49.95 cm, pelvic inlet area <333.2 cm^2, pelvic volume <7799.2 cm^3) had 2.8 to 3.5 times greater incidence of overall dystocia (19.0–20.8%) compared to heifers with a larger pelvis (incidence of 7.0–7.6%). Regarding calf factors, sex (male calves), body weight, chest circumference and fetlock joint circumference significantly increased the odds of experiencing dystocia due to fetopelvic disproportion compared with female, lighter or smaller calves. In a backward elimination model with independent variables treated as continuous, an area under the ROC curve of 0.66 regarding the prediction of overall dystocia based on heifer pelvic length, and of 0.64 for the prediction of fetopelvic dystocia based on fetlock joint circumference was found. The combination of the two variables in one model improved the ROC area to 0.71 regarding dystocia due to fetopelvic disproportion, reaching acceptable level of discrimination. Our findings indicate that dystocia due to fetopelvic disproportion in heifers is mainly influenced by the fetal side. Additionally, the estimation of pelvic dimensions of the dam before parturition and specific conformation characteristics of the calf during parturition, especially fetlock joint circumference, could aid obstetricians and herdsmen regarding dystocia probability and parturition surveillance.

Societies nowadays prioritize profits from livestock production in different ways than they used to do some decades ago. Many modern farmers evaluate equally welfare and profit and implement management practices to ensure ethical production (Krueger *et al.*, 2020). Dystocia, the inability to spontaneously deliver a calf, is a significant welfare issue because of the associated pain (Huxley and Whay, 2006), and affects longevity, reproduction and milk production (Berry *et al.*, 2007; Eaglen *et al.*, 2011). Dystocia also affects the welfare of the calf, and it impairs its vigour (Barrier *et al.*, 2012), overall health and survival (Mee, 2008). Despite the advancements made regarding calving management, dystocia remains a significant issue with estimated incidence between 10 and 50% (Crociati *et al.*, 2022).

Dystocia can be the result of various complications, and parity plays an important role in its pathogenesis. Primiparous cows have threefold the odds of experiencing dystocia compared with multiparous (Mee *et al.*, 2011; Dhakal *et al.*, 2013; Hiew *et al.*, 2016). They suffer predominately from fetopelvic disproportion (FPD) dystocia, which occurs as a consequence of a large calf, a small pelvis, or the combination of the two (Mee, 2008; Parkinson *et al.*, 2019). Based on recent literature it is estimated that 44% of dystocia in primiparous cows (De Amicis *et al.*, 2018) and 24% of overall dystocia (Johanson and Berger, 2003) can be attributed to FPD. However, most research regarding bovine dystocia does not differentiate between various causes of dystocia, thus resulting in bias (Olson *et al.*, 2009; Mee *et al.*, 2011; Dhakal *et al.*, 2013; Hiew *et al.*, 2016).

Calf birth weight and conformation are significant factors that affect dystocia (Johanson and Berger, 2003; Bureš *et al.*, 2008; Zaborski *et al.*, 2009; Kolkman *et al.*, 2010). Calf birth weight is the most common variable used to estimate fetal size in research studies

(Johanson and Berger, 2003; Mee, 2008; Mee *et al.*, 2011; Dhakal *et al.*, 2013). Similarly, the dimensions of the head (Colburn *et al.*, 1997; Olujohungbe *et al.*, 1998), the shoulders, the thorax in the region of cranial sternum (Colburn *et al.*, 1997; Kolkman *et al.*, 2010; Becker *et al.*, 2011) and the hip (Colburn *et al.*, 1997; Kolkman *et al.*, 2010) are considered as the most obstetrically relevant variables, and therefore critical for parturition (Bureš *et al.*, 2008; Becker *et al.*, 2011). However, there is insufficient evidence regarding the direct relationship between these variables and dystocia incidence, mainly because they cannot be measured ante-partum and there is no accurate method to predict them (Vincze *et al.*, 2018). Hence, researchers have focused on the correlations between the obstetrically relevant variables with those accessible during parturition, specifically head circumference and fetlock joint size, with controversial findings (Colburn *et al.*, 1997; Bureš *et al.*, 2008; Hiew *et al.*, 2016). As calf size and conformation are expected to affect dystocia primarily due to FPD, the relationships between these parameters specifically in primiparous cows can yield interesting results.

The size of the pelvis can also affect fetopelvic dystocia and it is influenced by the dam's age and body growth at parturition (Ali *et al.*, 1984; Holm *et al.*, 2014; Parkinson *et al.*, 2019). In most of the research articles, inner pelvic dimensions have been measured with the Rice pelvimeter or have been estimated by equations that presuppose that a pelvis has a perfect geometric shape (Holm *et al.*, 2014; Hiew *et al.*, 2016). However, based on previous studies (Tsousis *et al.*, 2010), these equations tend to underestimate pelvic dimensions. Additionally, measuring with the Rice pelvimeter is laborious and invasive, has measurement limitations (Hiew *et al.*, 2016) and high inter-observer variability (Vernooij *et al.*, 2020), which makes it rather unsuitable for use by farmers. Tsousis *et al.* (2010), with the aid of computed tomography, derived mathematical equations for the estimation of the inner pelvic dimensions based on easily accessible external measurements. In this study, r^2 was 0.8 for the estimation of pelvic area, circumference and volume. However, the relationship between those easily computed inner pelvic dimensions and dystocia incidence has not yet been investigated.

As dystocic cows have 2.9 higher odds of re-experiencing the condition in the future (Mee *et al.*, 2011), pre-partum prediction models can be of great value. The aim of this study was to investigate the association between dam and calf factors with overall dystocia incidence and incidence due to fetopelvic disproportion of primiparous cows. Within this context probability plots and ROC curves for dystocia incidence were applied based on the relationships between pelvic dimensions and calf's body measurements.

Materials and methods

Ethical statement

This study was approved by the Research and Ethics Committee of the Faculty of Veterinary Medicine, Aristotle University of Thessaloniki (1182/08.03.2018). All procedures complied with the EU Directive 2010/63/CE.

Animals and housing

The study was conducted at four dairy farms located in the region of Central Macedonia, Greece, around lake Koroneia, from 14/9/2018 to 6/8/2020. During the study period, 402 heifers and their calves were measured ($n = 229$, 72, 55 and 46 on the four farms, respectively).

Heifers were all of the Holstein breed and were housed primarily in open feedlots or bedded pack barns on straw, with minimum allowance of 10 m^2/animal. All were fed twice daily and had ab libitum access to water. All heifers were served exclusively by artificial insemination from the age of 13 months with commercially available sex sorted (initial two AIs) and conventional semen (thereafter) from Holstein bulls. Pregnancy diagnosis was performed *via* transrectal ultrasonographic examination, 30–45 d p.i. According to each farm's record, approximately 20 d before the expected calving, heifers were moved to the close-up group, which served as calving and long-stay maternity pen. Further details regarding study herds and feeding are provided in the online Supplementary file.

Study design: Calving management

During working hours (5 a.m.–10 p.m.), the animals were frequently observed for signs of imminent calving due to the proximity of the milking parlors. From 10 p.m. to 5 a.m. farm staff visited the maternity pen twice, approximately with an interval of 3.5 h, unless a cow had signs of imminent calving by the end of working hours, in which case surveillance was performed hourly. Herdsmen and staff were trained to recognize the following signs: swelling vulva, frequent changes in standing and recumbent position, restlessness, uplifting and relaxation of the tail, relaxation of the pelvic ligaments and udder filling. The staff discreetly monitored parturition. In case of lack of progress one hour after the appearance of amnion, they proceeded with a careful examination of the genital tract and the fetus. In the case of normal findings (sufficient dilation of vulva, cervix, normal presentation) an extra hour was provided to the animals to complete parturition. In cases of abnormal findings or after 120 min, the case was recorded as dystocia, and the intervention and the type of assistance was decided by the herdsmen, the farm staff or the farm veterinarian at that moment. Specific information and interventions during parturition were recorded by the herdsman after its completion. The recorded parameters and their definitions are provided in online Supplementary Tables S1 and S2. For the purposes of the present study only incidence of overall dystocia (OD) and incidence of dystocia due to fetopelvic disproportion (FPD: fetal oversize, small pelvis, fetomaternal disproportion or multiple etiology including FPD) were used.

Heifer measurements

Heifer anatomical parameters included in the study were primarily based on the results of Tsousis *et al.* (2010). Body measurements were conducted at 15 ± 11 (1–38) days ante-partum. Heifers were gently restrained in a headlock at close-up group with the aid of the farm staff, while the lead author performed measurements on the right side of the animal (Tsousis *et al.*, 2010). A custom-made caliper was used to measure externally the hip width, pin bones width and hip length. Body weight was calculated indirectly using a heart-girth measuring tape (WIN TAPE®) (Heinrichs *et al.*, 2007). The same tape was used for the calculation of chest circumference. Body condition score was determined on a 5-point scale (Edmonson *et al.*, 1989). All measurements were performed twice and exclusively by the lead author. The recorded parameters and their definitions are presented in online Supplementary Table S3.

Additionally, we applied equations to estimate the internal dimensions of the pelvises. Specifically, pelvic area (PA, cm^2), circumference (PC, cm), volume (VOL, cm^3), right diagonal of pelvic inlet (Diar, cm) and minimum height (Hmin, cm) were estimated (Tsousis *et al.*, 2010).

Calf measurements

Calf body measurements were performed within 24 h postpartum, except body weight, which was measured before the consumption of the first meal of colostrum (i.e. within two hours after parturition). The measurements were performed by the lead author using a 150-centimeter measuring tape with one-millimeter increments (Hoechstmass®, Wiesenstraße 13, 65843 Sulzbach, Germany), a 0–300 mm metallic caliper (Inter®, China) and an electronic scale with maximum weighing capacity 150 kg in 50 g increments. All measurements were performed twice. The recorded parameters and their definitions are presented in online Supplementary Table S4.

Statistical analyses

Statistical analyses were performed with SAS version 9.4 (SAS Institute Inc., 1996, Cary, NC, USA). All independent variables were initially tested for normality using the Shapiro–Wilk test, all followed a normal distribution, and the smallest quartile regarding pelvic and the largest quartile regarding calves' measurements were computed. Independent variables were then transformed into categorical based on the derived quartile values. The variables unrelated to dimensions (age at first calving – AFC, pregnancy duration – PrDur, Body Condition Score – BCS, and calves' body weight – BWC) were transformed into categories based on normal values for the Holstein Friesian breed and on bibliographical data (Noakes *et al.*, 2019). The associations between dependent (OD, FPD) and independent categorical variables were performed with χ^2 analysis. Moreover, associations between dependent (OD, FPD) and independent continuous variables were analyzed using a logistic regression with a binary distribution (PROC LOGISTIC). Independent variables' association with OD and FPD were first assessed in univariate models, after which significant ($P < 0.05$) independent variables were combined in a multivariable model, of which non-significant variables were removed using backward selection. Logistic regression was also used to derive ROC curves and predicted probabilities. Pelvic volume, PC, Diar and Hmin were not included in the multivariate model as they are a linear combination of other variables. Significance level was set at $P < 0.05$.

Results

During the study period, 402 heifers and their calves were measured. The incidence of OD was 10.4% ($n = 42$), of which half (5.2%, $n = 21$) was attributed to FPD. Specifically, 3% of calvings were attributed to an oversized calf ($n = 12$), 1% to a small pelvis ($n = 4$), 0.5% ($n = 2$) to both conditions and 0.75% ($n = 3$) were cases with multiple dystocia etiology including FPD. Of the remaining cases (5.2%, $n = 21$), 4% ($n = 16$) were due to insufficient vulva dilation, 0.75% ($n = 3$) due to uterine inertia and 0.5% ($n = 2$) due to abnormal posture.

Regarding heifer factors affecting OD (Table 1), pelvic volume was the most influential factor, as a heifer with a pelvic volume <7799 cm^3 had 3.5 times greater odds of experiencing dystocia compared with heifers with greater pelvic volume. The incidence of OD for heifers with pelvic area <333.2 cm^2 and pelvic circumference <69.86 cm was 19.0% compared to 7.7% in heifers with wider inlet. External pelvic parameters, specifically hip width, hip length, and pin bones width were also significant for OD. Moreover, chest circumference influenced dystocia incidence, as heifers with circumference <188 had OD of 16.7% vs. 8.3% in those with a wider chest. Pregnancy duration and body condition score did not influence OD incidence. Hip length was the unique heifer anatomic variable that also affected dystocia due to fetopelvic disproportion (online Supplementary Table S7). Interestingly, regarding AFC, the highest incidence of dystocia, both OD and due to FPD, was evident in the heifers that gave birth in the middle quartiles (24–28 months).

Regarding calf factors, there were no significant associations between the recorded parameters and the incidence of OD (online Supplementary Table S8), whereas sex, body weight, chest circumference, fetlock joint circumference and width influenced incidence of FPD (Table 2). Incidence of FPD in male calves was 9.7% (11 out of 113) compared to 3.5% (10 out of 288) in females. Calves lighter than 42 kg had a lower risk of FPD than heavier ones. Calves with a fetlock joint circumference greater than 18 cm had 4 times higher odds of FPD, while the incidence of FPD in calves with FJW greater than 5.45 cm was 9% vs. 4% in calves with narrower joints.

When heifer PA, PC, VOL and Hmin and calf CCC, FJC and HC were combined into ratios, PC/CCC and VOL/FJC were statistically significant for both OD and FPD ($P < 0.01$) (online Supplementary Tables S9 and S10). Regarding OD, VOL/HC and Hmin/HC additionally affected dystocia incidence (online Supplementary Table S9).

Logistic regression analysis, with independent variables treated as continuous, revealed a significant effect of TcTcH, TcTiH, CCH, PA, PC, VOL, Diar, and Hmin ($P < 0.01$) regarding overall dystocia, with the respective ROC area under the curve between 0.64 and 0.68. However, the combination of the above factors in a multivariable logistic regression model did not improve the prediction of dystocia. In a backward elimination process, pelvic length was the last variable remaining in the model (ROC area 0.66, Fig. 1). Pelvic volume showed the highest ROC (0.68) and probability values, but together with PC, Diar and Hmin were not included in the multivariate model as they are a linear combination of other variables.

Dystocia due to fetopelvic disproportion was significantly affected by FJC, FJW and calf body weight ($P < 0.05$). Additionally, a numerical but non-significant tendency was evident regarding HC and TcTcC. Again, multivariate analysis did not improve the prediction of the models. In a backward elimination analysis, only FJC remained significant (ROC area 0.64, Fig. 2).

All ratios used in the initial analysis (PA_CCC, VOL_FLJ, PC_CCC, Hmin_HC, VOL_HC) were significant ($P < 0.05$) and showed ROC values between 0.63 and 0.67. A model including both maternal TcTiH (OR and 95% C.I.: 0.80, 0.68–0.94) and calf FJC (OR and 95% C.I.: 2.2, 1.3–3.7) improved the ROC area to 0.71 regarding dystocia due to fetopelvic disproportion (online Supplementary Fig. S1A). Replacement of FJC with its body weight further improved ROC area to 0.76 (online Supplementary Fig. S1B).

Discussion

The present study is one of the few focusing on dystocia due to fetopelvic disproportion in dairy heifers. Actual body

Table 1. Heifer factors included in the statistical analysis regarding overall dystocia

Parameter	Level	*n*	OD[a] (%)	OR[b] (95% CI[c])	*P*-value
AFC (days)	<734	99	8.1	1.7 (0.5–5.2)	0.03
	734–847	199	14.6	3.2 (1.2–8.6)	
	>847	99	5.7	Ref.	
PrDur (days)	<275	151	9.9	0.9 (0.4–1.8)	0.93
	275–280	187	11.2	Ref.	
	>280	58	10.3	0.9 (0.3–2.4)	
BCS	<3	111	15.3	1.9 (0.9–3.7)	0.14
	3–3.5	214	8.9	Ref.	
	>3.5	76	7.9	0.9 (0.3–2.3)	
TcTcH	<49.95	98	19.4	2.9 (1.5–5.7)	0.009
	≥49.95	304	7.6	Ref.	
TcTi	<53	98	17.4	2.3 (1.2–4.5)	0.01
	≥53	304	8.2	Ref.	
TiTiH	<33.7	94	17.0	2.2 (1.1–4.4)	0.02
	≥33.7	308	8.4	Ref	
CCH	<188	96	16.7	2.2 (1.1–4.4)	0.02
	≥188	303	8.3	Ref.	
PA	<333.2	100	19.0	2.8 (1.4–5.4)	0.002
	≥333.2	297	7.7	Ref.	
PC	<69.86	100	19.0	2.8 (1.4–5.4)	0.002
	≥69.86	297	7.7	Ref.	
VOL	<7799.2	101	20.8	3.5 (1.8–6.7)	<0.0001
	≥7799.2	301	7.0	Ref.	
Diar	<20.24	101	18.8	2.8 (1.5–5.4)	0.002
	≥20.24	301	7.6	Ref.	
Hmin	<16.84	101	18.8	2.8 (1.5–5.4)	0.002
	≥16.84	301	7.6	Ref.	

[a]OD, Overall dystocia; [b]OR, Odds ratio; [c]CI, Confidence interval.

AFC, Age first calving; PrDur, Pregnancy duration; TcTcH, Heifer's hip width; TcTi, Hip length; TiTiH, Heifer's pin bones width; CCH, Heifer's chest circumference; PA, Pelvic inlet area; PC, Pelvic inlet circumference; VOL, Pelvic volume; Diar, Right diagonal of pelvic inlet; Hmin, minimum height.

measurements of dams and calves, with minimally invasive, field applicable equipment, were performed by the same person in four farms to reduce measurement error. Fetopelvic disproportion is considered the primary cause of dystocia in heifers, whereas it is the second most frequent reason of dystocia in cows (Mee, 2008). Inevitably, dystocia characteristics were estimated by farm personnel and veterinarians, which could result in bias. Nevertheless, all participants were long-term employees, had many years of experience regarding dystocia management and were adequately trained in the documentation of parturition characteristics by the lead author at the initiation of the study. Additionally, in our study measurements in calves were performed post-partum. As such, this study principally describes associations rather than being actual dystocia predictions. However, measuring calves during parturition could interfere with the normal calving process, cause iatrogenic bias in the results and have welfare implications.

One major finding of our study was that variables attributed to the maternal side primarily affected cases of OD but not those due to FPD. A possible explanation for these results is that the second major cause of dystocia in our study was incomplete dilation of the vulva, with an incidence rate of 4% (16 out of 21 dystocia cases of not fetopelvic origin). Vulval stenosis is more common in heifers and has a primarily hormonal background. It is attributed to inadequate concentration of pre-calving estrogens (estradiol 17-β) and a high cortisol to progesterone ratio, which in turn influences the relaxation of pelvic ligaments and the dilation of cervix and vulva (Mee, 2008; Parkinson *et al*., 2019). There is scarce evidence in the literature regarding vulval stenosis in dairy heifers. A narrow pelvis may be indirectly associated with vulval stenosis. The pubic symphysis and the iliac-sacral junctions are also subjected to the peripartal hormonal changes and relaxation. We hypothesize that inadequate vulval relaxation can be indicative of a contemporaneous poor relaxation of these structures and predisposition to dystocia, especially in heifers with smaller pelvises, as the available space in these dams is critical. Heifers with vulval stenosis had significantly smaller pelvises

Table 2. Calf factors included in the statistical analysis regarding fetopelvic disproportion dystocia

Parameter	Level	*n*	FPD (%)	OR[a] (95% CI[b])	*P*-value
Sexed semen	No	144	6.3	1.3 (0.5–3.2)	0.52
	Yes	252	4.8	Ref.	
Sex	Male	113	9.7	3.0 (1.2–7.3)	0.01
	Female	288	3.5	Ref.	
HC	≥49.5	92	7.6	1.7 (0.7–4.5)	0.24
	<49.5	310	4.5	Ref.	
CRL	≤87.13	300	5.3	1.1 (0.4–3.0)	0.90
	>87.13	100	5.0	Ref.	
CCC	>80	96	10.4	3.1 (1.3–7.5)	0.01
	≤80	304	3.6	Ref.	
TcTcC	>16.95	96	6.3	1.3 (0.5–3.4)	0.61
	≤16.95	305	4.9	Ref.	
TiTiC	>11.65	96	5.2	1.0 (0.4–2.8)	0.98
	≤11.65	304	5.3	Ref.	
FJC	>18	49	14.3	4.0 (1.5–10.5)	0.002
	≤18	352	4.0	Ref.	
FJW	>5.45	100	9.0	2.4 (1.0–5.8)	0.05
	≤5.45	301	4.0	Ref.	
BWC	≥42	86	10.5	2.9 (1.2–7.1)	0.02
	<42	308	3.9	Ref.	

[a]FPD, Fetopelvic dystocia; [b]OR, Odds ratio; [c]CI, Confidence interval.
HC, Head circumference; CRL, Crown rump length; CCC, Calf's chest circumference; TcTcC, Calf's hip width; TiTiC, Calf's pin bones width; FJC, Fetlock joint circumference; FJW, Fetlock joint width; BWC, Calf's birth weight

compared to the rest of the heifers (online Supplementary Table S11). Additionally, when a heifer experiences dystocia due to vulval stenosis, probably any additional cause of dystocia (for instance, a concurrent marginal pelvic size) could have been underestimated or overlooked by the personnel offering obstetrical help. Thus, we cannot exclude the possibility that at least part of the dystocia cases attributed to vulval stenosis also had FPD problems. More targeted studies are necessary to investigate these hypotheses.

Both external pelvic dimensions measured directly, and internal pelvic dimensions derived from equations proved significant regarding OD. As a general remark, heifers with smaller pelvises had 2–3 times greater incidence of dystocia compared to larger framed animals. Pelvic volume was the variable that was associated with the highest number of dystocic heifers. Nevertheless, the difference with pelvic width, which is much simpler to evaluate, was marginal. This is the first study where a significant relationship between pelvic volume and dystocia incidence in dairy cows is reported. Pelvic length was also a significant factor in our study for both OD and FPD. This result is in accordance with Ali *et al.* (1984), who found a genetic correlation between pelvic length and calving ease, indicating that a long pelvis favors easy calvings. Additionally, in this study (Ali *et al.*, 1984), pin width had the same genetic effect with pelvic length on calving ease. This variable was an important factor for dystocia in our study and that of Hiew *et al.* (2016). Although using different means of estimation, Hiew *et al.* (2016) also found that intrapelvic width and area in Holstein–Friesian heifers and cows were negatively correlated with calving difficulty score. This agrees with our results, as heifers belonging to the lowest quartile had 2.8 times more chances to experience dystocia compared to cows with larger pelvic area.

As the body conformation and weight of heifers show a strong correlation with age (Heinrichs and Hargrove, 1987; Hoffman, 1997), those that calve relatively young or without gaining the appropriate weight suffer more often from dystocia (Hoffman and Funk, 1992). However, in our study we found that heifers that calved at the age of 734–847 d (24–27.8 months) had higher odds of experiencing dystocia, both OD and FPD, compared with heifers that calved both older and younger. Our findings disagree with those of Ettema and Santos (2004), who failed to show any association between the age at first calving and calving difficulty score. Furthermore, Berry and Cromie (2009) and Steinbock *et al.* (2003) found a decrease in the proportion of heifers that required obstetrical assistance with an increase of the age at first calving from 22 to 24 and to over 26 months approximately. These discrepancies can be explained by the difference in the breeding management implemented in our study farms, which used predominantly sexed semen in the heifers at least for the first two AIs. As a result, heifers that conceived earlier and calved at an earlier age had more chances to birth a female calf. Indeed, 85.9% of the early AFC group (<734 d) gave birth to a female calf, compared to 71.4% of the medium AFC group and only 60.6% of the late AFC group. The fact that the late AFC group had lower

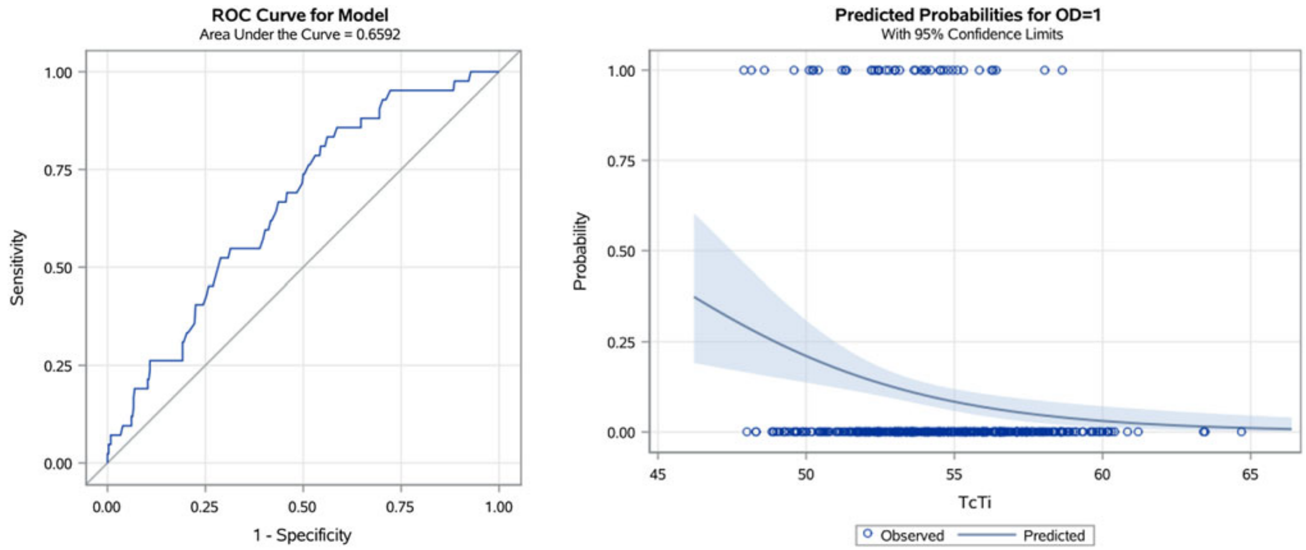

Figure 1. ROC curve and predicted probabilities (with 95% C.I.) for overall dystocia based on heifer pelvic length (TcTiH).

OD compared to the medium AFC in spite of a higher incidence of male born calves is indicative of a protective effect of high AFC on dystocia incidence (Steinbock *et al.*, 2003; Berry and Cromie, 2009). Hence, a breeding strategy aiming for a female calf in heifers giving birth in an early AFC can reduce dystocia due to FPD to marginal levels (1% in our study).

Additionally, our study clearly demonstrated that calf birth weight and conformation are major contributing factors regarding dystocia due to FPD, but not OD in heifers. This finding highlights the need for future obstetrical studies to focus on the exact causes of dystocia instead of considering dystocia as one entity. Moreover, the fact that only a limited number of studies differentiate between dystocia causes and between primi- and multiparous cows, can explain agreements (Meijering, 1984; Gaines *et al.*, 1993; Colburn *et al.*, 1997; Johanson and Berger, 2003) and disagreements (Olson *et al.*, 2009; Mee *et al.*, 2011; Dhakal *et al.*, 2013) between our research and other obstetrical studies.

Calves that weighed 42 kg or more, had higher odds of experiencing FPD compared with lighter ones. Similarly, Johanson and Berger (2003) showed that an increase of 1 kg in calf's birth weight increases the odds of dystocia by 13%. Meijering (1984) found that calf birth weight is the most determinant factor regarding FPD and it explains phenotypic variance by 50%. Additionally, male calves had 3 times greater odds of experiencing fetopelvic dystocia than female ones, although calf's sex did not influence OD. Since overall dystocia was largely influenced by the incidence of vulval stenosis, which is of maternal origin, it is not expected to be influenced by calf factors. Johanson and Berger (2003) found that male calves had 25% higher odds for dystocia than females. The effect of calf sex on dystocia incidence may be attributed to the fact that male calves are heavier at birth (Olson *et al.*, 2009; Dhakal *et al.*, 2013), partly due to longer gestation period (Olson *et al.*, 2009; Dhakal *et al.*, 2013), and they differ morphologically compared to female calves (Kolkman *et al.*, 2010).

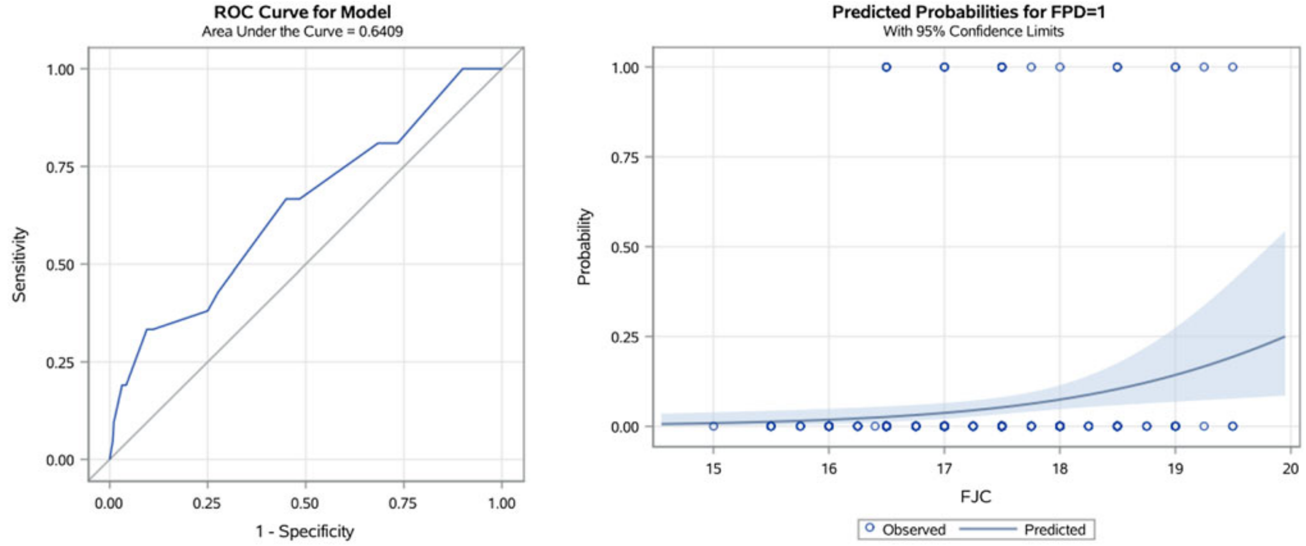

Figure 2. ROC curve and predicted probabilities (with 95% C.I.) for feto-pelvic dystocia based on fetlock joint circumference (FJC).

Although calf sex was a statistically significant factor regarding FPD, the use of sexed semen did not influence the incidence of OD nor FPD. However, Norman *et al.* (2010), analyzing a large dataset from the US, reported a significant reduction of dystocia incidence in Holstein heifers by the usage of sexed semen (from 6% to 4.3%). Interestingly, these results are very close to the incidence derived in our study (6.3% vs. 4.8%). Sexed semen may aid in the reduction of dystocia incidence because of the reduced number of male calves that are born (Seidel, 2007), but this effect progressively weakens due to the reduction of dystocia incidence, especially in clinical control studies involving smaller sample size.

Circumference of the fetlock joint affected FPD in our study. Similarly, Colburn *et al.* (1997) found that the circumference of fetlock joint was significantly larger between calves that needed caesarian section and those whose parturition was completed spontaneously. In previous studies (Becker *et al.*, 2011) we could only detect weak correlations between fetlock joint width and calf's body weight and no association with other obstetrically relevant dimensions. On the contrary, Hiew *et al.* (2016) did not find any association between hoof circumference and calving difficulty score but showed a good correlation with calf birth weight. Discrepancies between studies can be attributed to the use of different definitions of dystocia and to different handling of the data. In our opinion, the estimation of the fetlock joint can aid the prediction of oversized calves and dystocia, especially when its size exceeds certain limits (larger than 18 cm in our study). Future studies will further verify whether a pre-partum examination of the fetlock joint by ultrasound could offer true predictive value (Takahashi *et al.*, 2005). Additionally, the present study is, to our knowledge, the first to show a significant effect of calf chest circumference on FPD incidence. This finding agrees with the in vitro results of Becker *et al.* (2011) and Tsousis *et al.* (2011), who showed that the circumference of the thorax in the region of the cranial sternum in Holstein–Friesian calves is the largest and one of the most obstetrically relevant parameters.

Ratios are intended to combine heifer pelvic variables with calf body measurements to achieve better sensitivity in the prediction of dystocia. Hiew *et al.* (2016) found that the ratio of calf front hoof circumference to intrapelvic area correlated with the calving difficulty score, although hoof circumference was not a significant factor per se for dystocia. In our study, the applied ratios were significant for both OD and FPD. This finding can be explained by the fact that for the calculations of ratios, we opted for variables that were statistically significant in the univariate analysis. On the contrary, in most of the literature, the authors preferred variables that were considered biologically relevant with dystocia, specifically pelvic area and calf birth weight (Basarab *et al.*, 1993; Gaines *et al.*, 1993; Bureš *et al.*, 2008) or calf FJC (Hiew *et al.*, 2016). Nevertheless, the ratios used in our study did not offer additional information about dystocia compared to the initial analysis, probably in line with our main finding that maternal dystocia (in our case due to vulval stenosis) and fetopelvic dystocia (in our case due to an oversized calf) are two discrete biological conditions.

Multivariate analysis with measurements analyzed as continuous variables further supported the findings of the quartile analysis, as in most cases the same variables proved significant. Due to existing correlations between pelvic dimensions or between the anatomic parts of a calf, models ended up to a single explanatory variable. Receiver operating characteristic curves showed that a sufficient proportion of dystocia cases can be correctly classified ante-partum or at parturition by performing simple estimations. These results are to a large extent in agreement with the findings of Hiew *et al.* (2016), who found pelvic area and FJC to be the most significant factors to predict dystocia, with ROC values (0.78–0.81) similar to ours, although their study included both primi- and multiparous cows. On the contrary, Hiew *et al.* (2016) predicted probabilities for dystocia that were much higher than ours, due to much higher dystocia incidence (31.8% vs. 10.4%). From the graphical representation of dystocia probability, it was obvious that dystocia incidence followed an exponential function as pelvic dimensions become smaller (mainly regarding OD) and as calves become larger (mainly for FPD).

Although dystocia of dairy heifers is often attributed to fetopelvic disproportion, insufficient dilation of the birth canal posed a significant obstacle for delivery in our study, which could be related with pelvic dimensions. Based on our findings, dystocias classified as having a fetopelvic disproportion etiology probably originate more on the fetal side of the calving process and to a much lesser proportion to inadequate pelvic size. This finding emphasizes the importance for stakeholders to strive for small newborn calves.

In conclusion, many pelvic parameters were associated to a similar extent with overall dystocia incidence. Hence, farmers and obstetricians can be supported, even relatively distant (up to two weeks) from the upcoming calving, to adjust periparturient management in high-risk heifers. Additionally, in our opinion, measurement of the circumference of the fetlock joint of the fetus at term can be an applicable way to predict dystocia.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0022029923000468

Acknowledgments. This study is part of the dissertation thesis of the first author (AT), who is co-financed by Greece and the European Union (European Social Fund-ESF) through the Operational Program 'Human Resources Development, Education and Lifelong Learning' in the context of the Act 'Enhancing Human Resources Research Potential by undertaking a Doctoral Research' Sub-action 2: IKY Scholarship Program for PhD candidates in the Greek Universities". We would like to express our gratitude to all herdsmen for providing their farms to conduct the study and a special thanks to Mr. Kontozis Adam, DVM for his invaluable help with the measurements.

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