Impacts of Skeletal Muscle Depletion and Accretion Across Lactation

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Abstract

Skeletal muscle in dairy cattle plays a pivotal role in maintaining metabolic homeostasis, particularly during lactation when nutrient demands are heightened. Transition dairy cows experience negative energy and protein balances, leading to the mobilization of body tissues, to support maintenance, milk production, and fetal growth. Muscle depletion involves increased protein breakdown and decreased protein synthesis, with variability in the extent and timing of muscle mobilization across cows. The regulation of muscle breakdown is driven by multiple systems and is influenced by hormones like glucocorticoids and insulin. During lactation, muscle accretion occurs primarily through hypertrophy of existing muscle fibers. In a series of ultrasounds taken of cows from late gestation to early lactation, dairy cows can mobilize up to 40% of their longissimus dorsi muscle depth by 60 days in milk. However, muscle accretion is slower, and cows may not fully regain the muscle reserves they had at parturition by the end of lactation. Primiparous cows exhibit different patterns of muscle mobilization compared to multiparous cows, prioritizing muscle retention prepartum with similar mobilization postpartum. These findings show the importance of skeletal muscle in supporting cows in early lactation and highlight the need for further research into nutritional interventions to manage muscle reserves in the transition to lactation.

Introduction

Skeletal muscle is a dynamic tissue that serves as a reservoir of amino acids, which dairy cattle either accumulate or deplete throughout their production cycles. During the onset of lactation, dairy cows experience negative energy and protein balances, prompting them to mobilize body tissues, including adipose and muscle, to obtain the nutrients needed for maintenance, milk production, and growth (Bauman and Currie, 1980; Bell et al., 2000). Muscle depletion is a normal physiological adaptation to lactation, characterized by increased protein breakdown and decreased protein synthesis (Bauman, 2000). Enhanced proteolysis provides amino acids for the developing fetus in late gestation and supports the production of colostrum and milk in early lactation. This increase in protein breakdown is a normal homeorhetic response as animals adjust to their new requirements, despite insufficient intake to meet these needs. However, there is considerable variability in the extent and timing of muscle depletion across cows (van der Drift et al., 2012; McCabe et al., 2021; Gouveia et al., 2024). Moreover, the timing and extent of muscle accretion in dairy cattle are not well documented.

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Body Composition

Dairy cattle can lose between 3 and 17% of their body weight within the first five weeks postpartum (Zachut and Moallem, 2017). For example, a dairy cow weighing 700 kg postpartum could lose over 100 kg by the time they reach peak milk yield. Despite this, there is significant variation in body weight changes during early lactation, with some cows gaining weight as they approach peak milk yield. Cows that gain weight postpartum tend to have improved conception rates, though they show reduced milk yields in the first 30 days in milk (Zachut and Moallem, 2017). The variation in body weight loss is primarily due to differences in energy balance, as intake and milk production vary between cows. Even when cows consume the same diet and produce the same amount of milk, metabolic efficiencies differ, leading to varied body weight changes. Dairy cows are estimated to have 90 to 125 kg of empty body protein and a wider range of adipose tissue, from under 100 kg to more than 200 kg (Komaragiri and Erdman, 1997). Changes in body weight are caused by changes in both muscle and fat stores. Subcutaneous fat correlates strongly with body condition score (Wright and Russel, 1984) and total body fat (Schröder and Staufenbiel, 2006). In contrast, muscle depth shows only a moderate correlation with body condition score (Sloniewski et al., 2004; Siachos et al., 2021). This makes muscle depth more challenging to assess through visual observations than fat reserves.

Muscle Composition in Dairy Cattle

Skeletal muscle is the largest internal organ in dairy cattle and plays a crucial role in maintaining metabolic balance (Sadri et al., 2023). It is vital for posture, movement, and protection, and a baseline level of muscle is necessary for normal bodily functions. Muscle tissue stores amino acids, which can be utilized during periods when protein intake falls short. The role of amino acids from skeletal muscle varies throughout lactation. During early lactation, specific amino acids, particularly alanine and glutamine, are released from muscle and utilized by the liver to produce glucose (Overton et al., 1998; Drackley et al., 2001). However, in early lactation, amino acids are likely preferentially allocated to milk protein synthesis (Larsen et al., 2014; Larsen et al., 2015). Skeletal muscle has the highest insulin-stimulated glucose uptake among tissues and thus plays a significant role in maintaining insulin sensitivity, especially in transition cows, who often experience low circulating insulin levels and insulin resistance.

Skeletal muscle is a complex tissue made up of multinucleated contractile cells known as myofibers. Bovine skeletal muscle includes three main fiber types: Type I, Type IIA, and Type IIX, classified according to the specific myosin heavy chain proteins present (Hoh, 2023). Type I fibers are slow-twitch, fatigue-resistant fibers with higher levels of oxidative enzymes, myoglobin, and mitochondria. Type IIX fibers, on the other hand, are fast-twitch and rely heavily on glycolytic metabolism. Type IIA fibers lie in between, having both oxidative and glycolytic properties (Schiaffino and Reggiani, 1994). These muscle fibers show a high degree of plasticity and can shift phenotypically between types I, IIA, and IIX (Cicilot et al., 2013). As a result, hybrid fiber types (I/IIA and IIA/IIX) may appear, especially during stress periods. Muscle fiber composition varies based on the skeletal muscle group's physiological needs, with different types dominating depending on muscle location. For instance, the *semitendinosus* (eye of round) predominantly contains Type II fibers, while the *psoas major* (tenderloin) is rich in Type I fibers (Lang et al., 2020). Thus, the specific location of a muscle sample significantly influences its fiber composition. Given the distinct characteristics of muscle fibers, some fibers may preferentially degrade during catabolic processes, while others are preserved, although this is still an area of active research.

Muscle Depletion

The regulation of muscle breakdown occurs through three interconnected systems: autophagy-lysosomal, calpain calcium-dependent cysteine proteases, and the ubiquitin-proteasomal system (Sadri et al., 2023). These systems work together to maintain protein balance, each playing a specific role in muscle degradation. External endocrine signals, such as insulin, growth hormone, IGF-1, and glucocorticoids can trigger increased muscle catabolism. In early lactation, muscle's response to insulin is reduced, and elevated levels of glucocorticoids and glucagon can have a catabolic effect, further promoting muscle breakdown (Sadri et al., 2023). Skeletal muscle experiences constant turnover, with simultaneous protein catabolism and anabolism. During the periparturient period, there is an upregulation of proteolytic pathways and a decrease in protein synthesis (Ghaffari et al., 2019).

Muscle Accretion

Skeletal muscle growth occurs through protein accretion, myonuclear accretion, and the accumulation of extracellular matrix (Allen et al., 1979). Muscle accretion happens when the rate of protein synthesis surpasses protein breakdown (Goll et al., 2008). Skeletal muscle can regenerate in response to growth through the activation of satellite cells (Brack and Rando, 2012; Relaix et al., 2021). The number of satellite cells, and thus the regenerative capacity of muscle, is set during the late fetal stage (Brack and Rando, 2012). After birth, the number of muscle fibers remains relatively constant, and growth occurs due to hypertrophy of existing fibers rather than an increase in fiber number. In adults, satellite cells remain dormant until stimulated by factors like exercise or injury, after which they help repair or regenerate muscle. The major anabolic pathway controlling protein synthesis is the mTOR signaling pathway (McCarthy and Esser, 2010). Protein synthesis responds to several factors, including growth factors, hormones, cytokines, oxidative stress, metabolic stress, and nutrient availability (McCarthy and Esser, 2010). These factors interact, meaning that an animal's nutritional status can influence growth factors and thereby impact muscle growth (Thornton, 2019). Thus, certain stages of lactation may see more pronounced muscle growth in response to nutritional changes, depending on the signaling environment at the time.

Assessment of Tissue Reserves and Mobilization

In early lactation, both adipose and protein stores are depleted, with skeletal muscle being the primary source of protein mobilization. Botts et al. (1979) estimated that around 27% of empty body protein is mobilized in protein-restricted diets designed to achieve a nitrogen balance of 0. When more dietary protein is available, lower amounts of protein are mobilized, with approximately 20% of empty body protein being used (Komaragiri and Erdman, 1997; van der Drift et al., 2012). For transition dairy cows, depending on their body condition score, adipose tissue may account for over 25% of empty body weight, while protein represents about 13% (Komaragiri and Erdman, 1997). Metabolic adaptation during lactation can lead to the mobilization of more than 80 kg of adipose tissue and 20 kg of protein. In comparison to other livestock species, skeletal muscle estimates in dairy cattle, particularly for healthy, productive lactating cows, are not well documented. Slaughter studies across lactation stages provide detailed body composition data, including muscle changes. However, due to the high resource commitment involved in such studies, alternative methods have been developed for approximating skeletal muscle mass.

Metabolites related to skeletal muscle metabolism, such as creatinine and 3-methylhistidine **(3-MH)**, are used to estimate muscle mass and proteolysis. Creatinine, a byproduct of muscle metabolism, is produced at a constant rate from the breakdown of creatine and phosphocreatine (Wyss and Kaddurah-Daouk, 2000). Higher creatinine concentrations correlate with more muscle mass, while lower concentrations reflect muscle mobilization after periods of extensive muscle breakdown (Megahed et al., 2019). Similarly, 3-MH, an amino acid found in actin and myosin, is released during muscle degradation and cannot be reincorporated into muscle, making it a marker of muscle degradation. Since muscle is constantly undergoing breakdown and synthesis, 3-MH is always present, but relative changes over time or between treatments can indicate the extent of protein degradation. To standardize measurements across animals, the ratio of 3-MH to creatinine can be used to assess relative differences in protein degradation per unit of muscle mass. A higher 3-MH:creatinine ratio indicates more protein breakdown.

Extent of Muscle Mobilization Using Ultrasound

In beef cattle, ultrasound measurements of the *longissimus dorsi* muscle depth is highly correlated with whole-body protein amounts (Greiner et al., 2003). In dairy cattle, ultrasound techniques have been applied to measure muscle depth in specific areas, such as the *longissimus dorsi* and *gluteus medius*, and these measurements can be used to estimate overall protein levels (van der Drift et al., 2012; Megahed et al., 2019). During the transition period, some individual dairy cows have been shown to mobilize over 40% of their *longissimus dorsi* muscle depth (McCabe et al., 2021). In several studies, ultrasound images of the *longissimus dorsi*, taken from six weeks prepartum to four weeks postpartum, show an approximate 33% reduction in muscle depth, indicating significant muscle mobilization during early lactation (i.e. McCabe et al., 2021; Gouveia et al., 2024).

Muscle mobilization begins before calving, primarily to provide amino acids for fetal development and support colostrum production. Muscle depth typically stabilizes around one month postpartum (van der Drift et al., 2012; McCabe et al., 2021). It is important to recognize that estimates of skeletal muscle depth also account for intramuscular fat. Therefore, reductions in muscle depth are due to both the reduction in muscle fiber size and the loss of intramuscular fat.

At Purdue University, a series of research trials collected ultrasound images of the *longissimus dorsi* starting 5 to 6 weeks before expected calving, continuing until 8 weeks into lactation (McCabe et al., 2021; Gouveia et al., 2024; Hanno et al., 2025). The study revealed considerable variation in muscle depth during the dry period, ranging from 2 to 6.5 cm. Cows with larger muscle reserves prepartum tended to mobilize more of their *longissimus dorsi* muscle depth by 60 days in milk and subsequently produced higher milk yields in early and mid-lactation (Gouveia et al., 2024; Hanno et al., 2025). This pattern is similar to what is observed with adipose tissue: cows with greater fat reserves tend to mobilize more adipose tissue during early lactation. van der Drift et al. (2012) reported that *longissimus dorsi* depth decreased prepartum and continued to decrease during the early weeks of lactation, while adipose tissue reserves are primarily mobilized after calving. Recently, we found that multiparous cows with greater muscle reserves during the far-off dry period lost muscle prepartum, while cows with fewer muscle reserves could actually gain muscle before calving (McCabe et al., 2021; Gouveia et al., 2024). These cows with larger muscle reserves also gave birth to heavier calves, likely due to the increased availability of amino acids supporting fetal growth.

Ultrasound images were collected from 40 multiparous cows monthly from parturition to 300 days in milk. Of the time points measured, the greatest *longissimus dorsi* depth was observed at parturition (Figure 1; adapted from Hanno, 2025). Following parturition, cows experienced a reduction in muscle depth until 60 days in milk, with no significant muscle gain occurring until around 270 days in milk. On average, cows mobilized 30 to 35% of their muscle reserves between parturition and 60 days in milk. By 300 days in milk, cows had not fully regained the muscle depth they had at parturition. Interestingly, even though cows began to gain body weight and adipose tissue post-peak (after 90 days in milk), they did not experience significant muscle accretion until much later in lactation. These findings suggest that as cows approach the dry period, they may have less muscle compared to what they had at parturition.

Studies conducted in primiparous animals indicate that they have similar, if not more, muscle depth than multiparous cows prepartum (data to be presented at ADSA 2025; Abstract # 93552 and 94019). However, one unique characteristic of primiparous animals is that they mobilized muscle depth just one week prior to calving and heifers with more muscle depth did not produce heavier calves. Postpartum, primiparous cows mobilize *longissimus dorsi* depth to a similar extent as multiparous cows. While we have observed similar results for muscle mobilization when comparing second parity to third and greater parity animals, it appears that primiparous animals may be prioritizing muscle differently prepartum and are capable of accreting a large amount of muscle as heifers that they draw on in early lactation. This is an active and still developing area of research.

Summary

Skeletal muscle in dairy cattle plays a critical role in maintaining metabolic homeostasis, particularly during lactation when cows experience muscle depletion to meet the increased nutritional demands for milk production and fetal growth. Muscle composition varies across different muscle groups, with three major fiber types (I, IIA, and IIX), each with distinct metabolic characteristics. Muscle mobilization in multiparous cows begins prior to calving and continues into early lactation, driven by elevated glucocorticoids and insulin resistance. Research has shown that cows with larger muscle reserves prepartum tend to mobilize more muscle early in lactation and produce higher milk yields, while cows with smaller reserves may gain muscle postpartum. Ultrasound studies indicate that cows lose muscle depth between parturition and 60 days in milk, with little muscle gain until later in lactation, even when cows are gaining weight and adipose tissue. At 300 days in milk, cows still had not regained the muscle depth present at parturition, suggesting a potential long-term impact of lactation on muscle reserves, particularly as cows approach the dry period.

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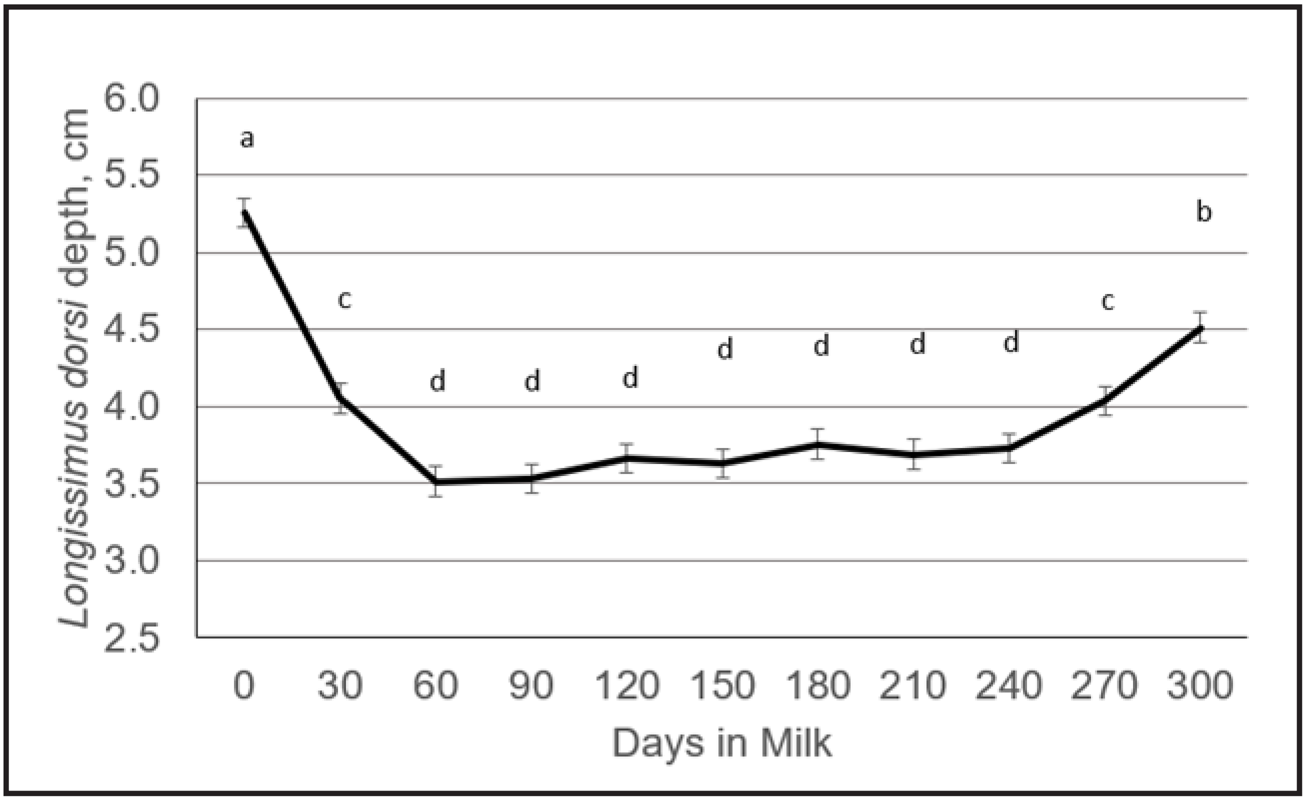

Figure 1. Longissimus dorsi depth from parturition to 300 days in milk (adapted from Hanno et al., 2025). Letters a – d indicate means were significantly different from one another.