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RESEARCH ARTICLE

Mechanical and molecular parameters that influence the tendon differentiation potential of C3H10T1/2 cells in 2D- and 3D-culture systems

Ludovic Gaut¹, Marie-Ange Bonnin¹, Cédrine Blavet¹, Isabelle Cacciapuoti², Monika Orpel¹, Mathias Mericskay³ and Delphine Duprez^{1,*}

ABSTRACT

One of the main challenges relating to tendons is to understand the regulators of the tendon differentiation program. The optimum culture conditions that favor tendon cell differentiation have not been identified. Mesenchymal stem cells present the ability to differentiate into multiple lineages in cultures under different cues ranging from chemical treatment to physical constraints. We analyzed the tendon differentiation potential of C3H10T1/2 cells, a murine cell line of mesenchymal stem cells, upon different 2D- and 3D-culture conditions. We observed that C3H10T1/2 cells cultured in 2D conditions on silicone substrate were more prone to tendon differentiation, assessed with the expression of the tendon markers *Scx*, *Col1a1* and *Tnmd* as compared to cells cultured on plastic substrate. The 3D-fibrin environment was more favorable for *Scx* and *Col1a1* expression compared to 2D cultures. We also identified TGFβ2 as a negative regulator of *Tnmd* expression in C3H10T1/2 cells in 2D and 3D cultures. Altogether, our results provide us with a better understanding of the culture conditions that promote tendon gene expression and identify mechanical and molecular parameters upon which we could act to define the optimum culture conditions that favor tenogenic differentiation in mesenchymal stem cells.

KEY WORDS: Mesenchymal stem cells, Cell confluence, cell cultures, Plastic substrate, Silicone substrate, Tendon differentiation, TGFβ2, Scleraxis, Tenomodulin

INTRODUCTION

Mesenchymal stem cells (MSCs) are multipotent cells that can be induced to differentiate in various tissue lineages upon specific molecular or mechanical cues. Based on specific lineage markers and identified master genes, established protocols are now recognized to drive differentiation towards osteocytes, chondrocytes and adipocytes (Caplan, 1991; Pittenger et al., 1999; Prockop, 1997). Although studies identify tendon cell

differentiation upon molecular and mechanical cues from MSCs (reviewed in Nourissat et al., 2015; Zhang et al., 2018), tendon lineage is less studied than other tissue-specific lineages. There is no recognized/established protocol with external inducers to differentiate MSCs towards a tendon phenotype. In addition, there is no identified master gene that initiates the tenogenic program in cell cultures as for the cartilage (*Sox9*), bone (*Runx2*) and muscle (muscle regulatory factors) programs (Buckingham, 2017; Karsenty et al., 2009; Liu et al., 2017).

Another difficulty in studying tendon differentiation is the limited number of specific tendon markers. The main structural and functional component of the tendon, type I collagen, is not specific to the tendon and is expressed in many other connective tissues (reviewed in Gaut and Duprez, 2016). To date, the bHLH transcription factor Scleraxis (*Scx*) is the best marker for tendons and ligaments during development (Schweitzer et al., 2001, 2010) and in the adult (Mendias et al., 2012). Although it is a powerful tendon marker, the exact function of *Scx* in tendon development, homeostasis and repair is still not fully understood (Huang et al., 2015; Murchison et al., 2007). The type II transmembrane glycoprotein tenomodulin, encoded by the *Tnmd* gene, is recognized to be a tendon differentiation marker with potential roles in tenocyte proliferation and differentiation in addition to type I collagen fibril adaptation to mechanical loads (Alberston et al., 2015; Dex et al., 2016, 2017; Docheva et al., 2005). *Scx* is required for *Tnmd* expression in mouse tendons during development (Murchison et al., 2007; Yoshimoto et al., 2017). *Scx* gain- and loss-of-function experiments combined with electrophoresis mobility shift assay (EMSA) in cell cultures indicate a direct regulation of *Scx* on *Tnmd* promoter (Shukunami et al., 2018; Yoshimoto et al., 2017). In addition to the well-studied tendon markers, *Scx* and *Tnmd*, a list of 100 tendon markers has been identified in limb tendon cells during mouse development via transcriptomic analysis (Havis et al., 2014).

The main extracellular signal known to promote tendon development is the TGFβ ligand (Havis et al., 2014, 2016; Maeda et al., 2011; Pryce et al., 2009). TGFβ ligands are recognized to have a generic tenogenic effect based on the increase of *Scx* transcription in cell cultures (Guerquin et al., 2013; Havis et al., 2014, 2016; Lorda-Diez et al., 2009; Pryce et al., 2009). The increase of *Scx* expression upon TGFβ2 exposure is abolished in the presence of TGFβ inhibitors, which block TGFβ signal transduction at the level of the receptors or at the level of the SMAD2/3 intracellular pathways in C3H10T1/2 cells (Guerquin et al., 2013; Havis et al., 2014).

In addition to chemical signals, mechanical signals are important parameters to consider when studying tendon cell differentiation. Because tendons transmit forces from muscle to bone in the

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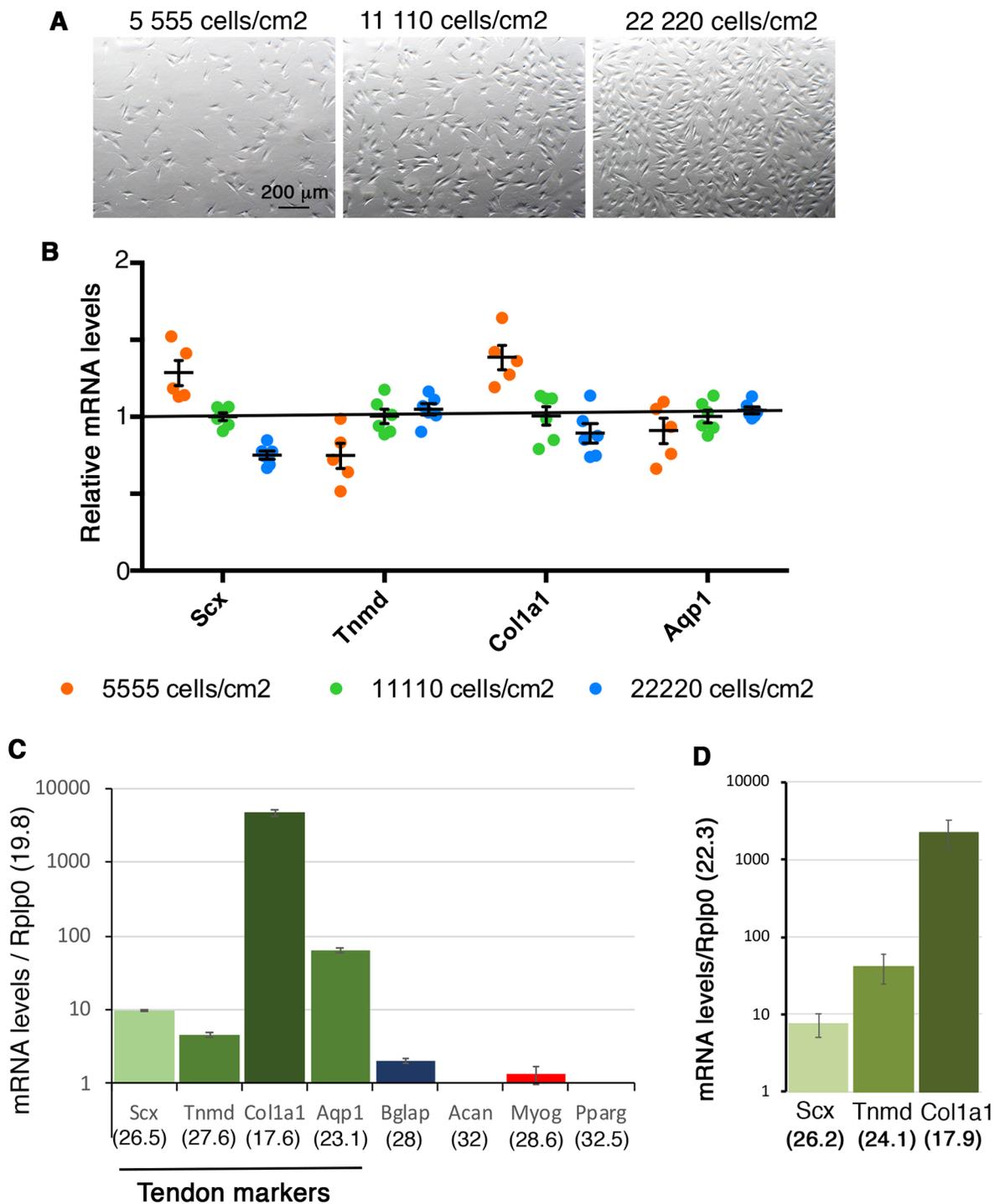


Fig. 1. Tendon gene expression is not related to cell density in non-confluent conditions. (A) Representative pictures of cell density 16 h after plating 0.5×10^5 (5555 cells/cm²), 10^5 (11,110 cells/cm²) and 2×10^5 (22,222 cells/cm²) C3H10T1/2 cells on 9 cm² plastic culture plates. (B) RT-qPCR analyses of the expression levels of tendon markers *Scx*, *Tnmd*, *Col1a1* and *Aqp1* in C3H10T1/2 cells 16 h after initial plating of 5555 cells/cm², 11,110 cells/cm² and 22,220 cells/cm². The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method using the 11,110 cells/cm² plating condition as control. For each gene, the mRNA levels of the 11,110 cells/cm² plating condition were normalized to 1 (green spots). Graph shows means \pm s.d. of six biological samples. (C) RT-qPCR analyses of the expression levels for the tendon markers *Scx*, *Tnmd*, *Col1a1*, *Aqp1* and for lineage markers, *Bglap* (bone), *Acan* (cartilage), *Myog* (muscle) and *Pparg* (fat) in C3H10T1/2 cells 16 h after initial plating 11,110 cells/cm² on plastic culture plates. mRNA levels on the Y-axis are reported to the *Rplp0* (*36b4*) gene ($2^{-\Delta Ct} \times 10^3$). Graph shows means \pm s.d. of six biological samples. The means of the initial Cts (obtained from 250 ng of mRNAs) are indicated in brackets for each gene. *Rplp0* (Cts=19.6 s.d. \pm 0.17); *Col1a1* (Cts=17.6 s.d. \pm 0.2); *Aqp1* (Cts=23.1 s.d. \pm 0.44); *Scx* (Cts=26.5 s.d. \pm 0.22); *Tnmd* (Cts=27.6 s.d. \pm 0.28); *Bglap* (bone, Cts=28 \pm 0.38); *Myog* (muscle, Cts=28.6 \pm 0.16). *Acan* (cartilage) and *Pparg* (fat) displayed Cts above 32. (D) RT-qPCR analyses of tendon gene expression levels in adult mouse tendons. For each gene, the ΔCt was calculated using *Rplp0* as a reference gene, $\Delta Ct = Ct \text{ gene} - Ct \text{ Rplp0}$. mRNA levels on the Y-axis are reported to the *Rplp0* (Cts=22.3 s.d. \pm 1) gene ($2^{-\Delta Ct} \times 10^2$). Graph shows means \pm s.d. of five biological samples. The means of the initial Cts (obtained from 150 ng of mRNA) are indicated in brackets for each gene. *Scx* (26.2 s.d. \pm 0.63) *Tnmd* (24.1 s.d. \pm 0.62) and *Col1a1* (17.9 s.d. \pm 0.57).

musculoskeletal system, tendon cells are continuously subjected to variations in their mechanical environment (Schiele et al., 2013). Physical constraints subjected to the cells have been shown to be important for developmental processes and during the adult life (Mammoto et al., 2013). It is recognized that substrate stiffness controls many cellular processes such as cell fate, migration, proliferation and differentiation in culture systems of stem cells or progenitor cells (Bellas and Chen, 2014; Ivanovska et al., 2015; Kilian et al., 2010). MSCs are particularly responsive to matrix stiffness in terms of lineage commitment, ranging from neurogenic phenotype for soft substrates to osteogenic when cultured on rigid

substrates (Discher et al., 2009; Engler et al., 2006; Humphrey et al., 2014). The forces transmitted through cell contacts upon confluence is another parameter that mechanically constrains cells in culture dishes and influences cell differentiation (Abo-Aziza and Zaki, 2017; Ren et al., 2015).

The tendon phenotype is not maintained in 2D-cultures of tendon cells over passages (Hsieh et al., 2018; Shukunami et al., 2018; Yao et al., 2006). 3D-culture systems in which tendon cells are embedded in hydrogels are recognized to provide an environment closer to that experienced by tendon cells *in vivo* (Kapacec et al., 2010; Kuo et al., 2010; Marturano et al., 2016; Yeung et al., 2015).

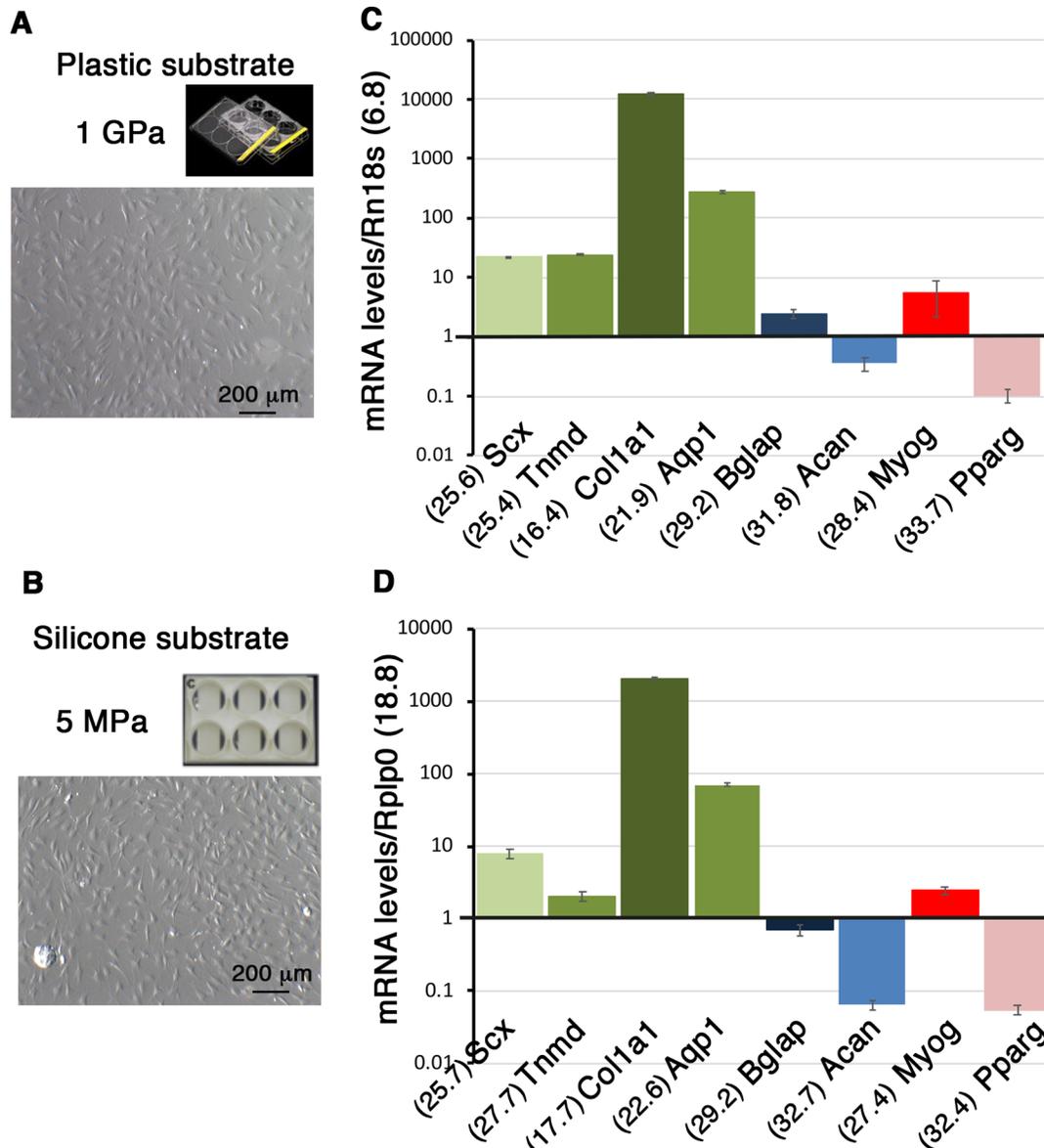


Fig. 2. The nature of the substrate does not modify gene expression profiles in C3H10T1/2 cells in non-confluent conditions. (A,B) Photographs of C3H10T1/2 cells cultured on plastic plates displaying a stiffness of 1 GPa (A) and on Uniflex culture plates made of silicon coated with type I collagen displaying a stiffness of 5 Mpa (B) in non-confluent conditions. (C,D) RT-qPCR analyses of gene expression levels in C3H10T1/2 cells. *Scx*, *Tnmd*, *Col1a1*, *Aqp1* and representative genes for the bone (*Bglap*), cartilage (*Acan*), muscle (*Myog*) and fat (*Pparg*) lineages in C3H10T1/2 cells in non-confluent conditions on plastic (C) and silicone (D) substrates. The means of the Ct's (obtained from 500 ng of mRNAs) are indicated in brackets for each gene. (C) Plastic substrate: for each gene, the ΔCt was calculated using *Rn18S* as a reference gene. $\Delta\text{Ct}=\text{Ct gene}-\text{Ct } Rn18S$. The mRNA levels were reported using the $2^{-\Delta\text{Ct}}$ method. In order to obtain values above 1, each $2^{-\Delta\text{Ct}}$ were multiplied per 10^6 . Graph shows means \pm s.d. of four biological samples. (D) Silicone substrate: for each gene, the ΔCt was calculated using *Rplp0* as a reference gene. $\Delta\text{Ct}=\text{Ct gene}-\text{Ct } Rplp0$. The mRNA levels were calculated using the $2^{-\Delta\text{Ct}}$ method. For each gene, $2^{-\Delta\text{Ct}}$ were multiplied per 10^3 . Graph shows means \pm s.d. of six biological samples.

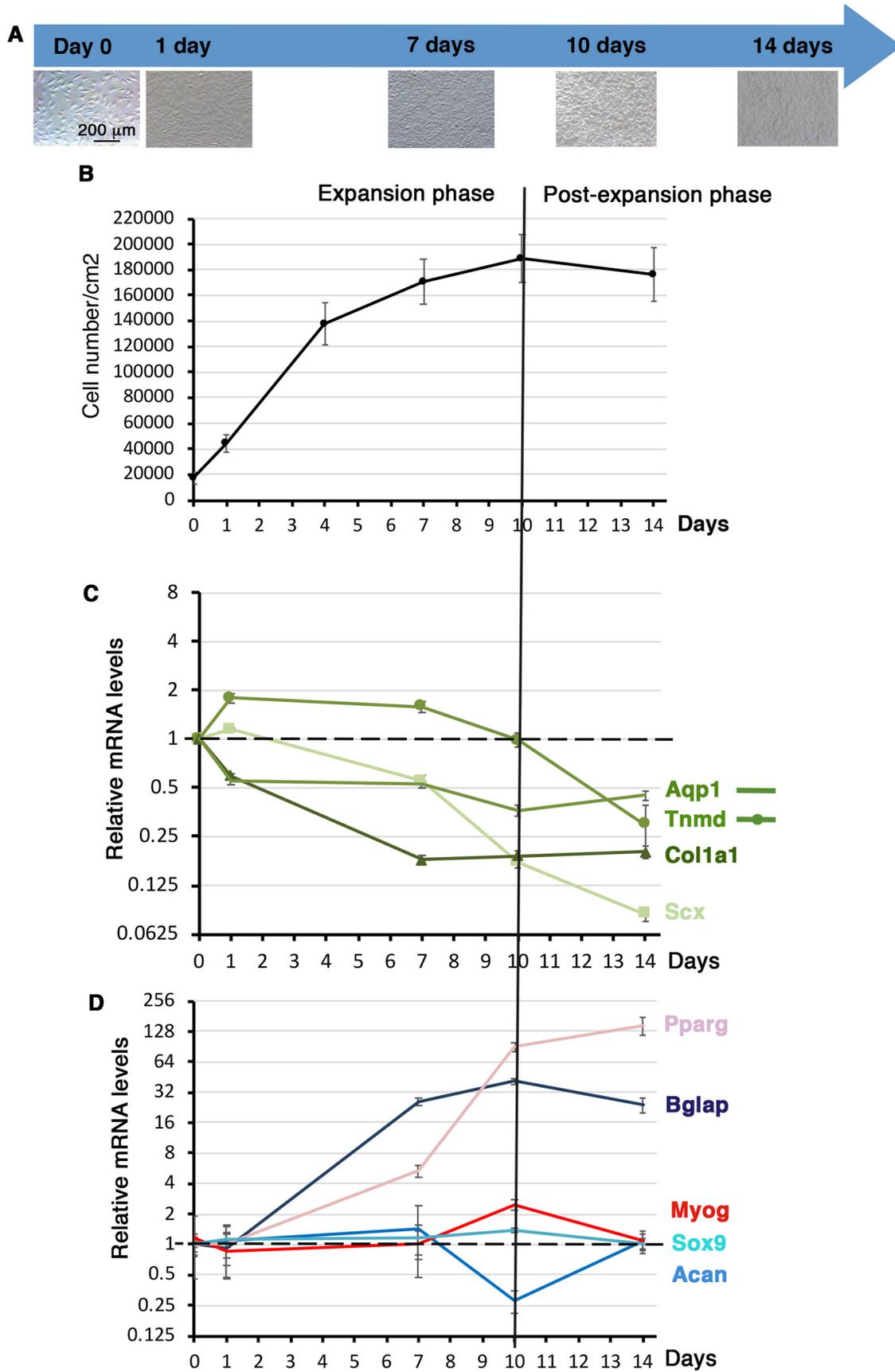


Fig. 3. See next page for legend.

Fig. 3. Gene expression in C3H10T1/2 cells cultured on plastic substrate over time. (A) Photographs of C3H10T1/2 cells cultured on plastic culture plates at different time points. 10^5 C3H10T1/2 cells were plated on plastic culture plates and left for 16 h to define the T=0 time point. Cells were then fixed at 1 day, 7 days, 10 days and 14 days for RT-qPCR analyses. (B) Cell density or cell number/cm² was measured at each time point. (C,D) RT-qPCR analyses of the expression levels for tendon genes, *Scx*, *Tnmd*, *Col1a1*, *Aqp1* (C) and other cell lineage markers, *Bglap* (bone), *Sox9* and *Acan* (cartilage), *Myog* (muscle) and *Pparg* (fat) in C3H10T1/2 cells cultured on plastic culture plates at different time points. Gene mRNA levels were normalized to *Rplp0*. The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method using the day 0 condition as control. For each gene, the mRNA levels of the T=0 condition were normalized to 1. Graphs show means \pm s.d. of four biological samples for T=0, 1 day, 7 days and 14 days and of five biological samples for 10 days.

The mechanical environment provided to tendon cells homogeneously embedded within hydrogel in 3D-culture systems is recognized to act on tendon gene expression (Hsieh et al., 2018; Marturano et al., 2016). Most of the analyses of the effects of 2D and 3D environments have been performed with tendon stem/progenitor cells; however, the optimum culture conditions that drive tendon cell differentiation from MSCs have not been yet identified. In the present study, we analyzed the tendon differentiation potential of C3H10T1/2 cells under different mechanical and molecular signals in 2D- and 3D-culture conditions.

RESULTS

In order to investigate tendon differentiation potential, we used C3H10T1/2 cells, a multipotent cell line established from mouse embryos (Reznikoff et al., 1973). C3H10T1/2 cells are known to differentiate into chondrocytes, osteocytes and adipocytes when cultured under appropriate cues (Guerquin et al., 2013). These cells have the ability to display a tendon phenotype under inductive molecular cues, such as the transcription factors EGR1 and MKX (Guerquin et al., 2013; Liu et al., 2015). The ability to differentiate into cell lineages related to the musculoskeletal system makes the C3H10T1/2 cells an ideal tool to study tendon commitment and differentiation under different mechanical and molecular cues in 2D- and 3D-culture conditions. To assess tendon differentiation, we used the mRNA levels of key tendon markers, *Scx* and *Tnmd*, in addition to *Colla1*, the main structural and functional tendon component. We also used tendon genes identified in the transcriptomic analysis of mouse tendon cells during development (Havis et al., 2014), such as aquaporin1 (*Aqp1*) gene coding for a water channel protein and thrombospondin 2 (*Thsb2*) coding for an adhesive glycoprotein with antiangiogenic properties, both expressed in developing limb tendons.

Seeding density does not affect tendon gene expression in non-confluent conditions after 16 h of culture

We first determined whether the initial cell number interfered with the expression of tendon genes in non-confluent conditions. Different amounts of cells (0.5×10^5 , 10^5 and 2×10^5) were seeded in 9 cm² culture plates (plastic substrate), corresponding to 5555 cells/cm², 11,110 cells/cm² and 22,220 cells/cm², respectively. After 16 h of culture, the expression of tendon genes, *Scx*, *Tnmd*, *Colla1* and *Aqp1* did not display any change more than 20% upon different cell density seeding conditions (Fig. 1A,B). This shows that the initial cell number at seeding time does not have a major influence on tendon gene expression in expansion and non-confluent conditions.

We next compared the relative mRNA expression levels between tendon genes in C3H10T1/2 cells in non-confluent conditions on plastic substrate in the 11,110 cells/cm² seeding condition (Fig. 1C).

The expression levels of each tendon gene were reported to the *Rplp0* gene (Ct=19.8 for 250 ng of RNAs). We found that the *Colla1* gene displayed high expression levels (Ct=17.6) compared to those of *Aqp1* (Ct=23.1), *Scx* (Ct=26.5) and *Tnmd* (Ct=27.6) genes in C3H10T1/2 cells in the non-confluent condition (Fig. 1C). Comparison with tendon gene expression in native adult mouse tendons indicated a similar tendency of high expression levels of *Colla1* gene compared to *Scx* and *Tnmd* (Fig. 1D). *Tnmd* was also more expressed than *Scx* in adult mouse tendons (Fig. 1D), highlighting *Tnmd* as a potent tendon marker as already reported (Takimoto et al., 2012). Analysis of the mRNA expression levels for other lineage markers showed that *Acan* (cartilage) and *Pparg* (fat) genes were not expressed (Ct above 32), while *Bglap* (bone, Ct=28) and *Myog* (muscle, Ct=28.6) genes displayed low levels of expression in C3H10T1/2 cells in non-confluent conditions on plastic substrate (Fig. 1C). This shows that tendon genes are expressed in C3H10T1/2 cells seeded in non-confluent conditions on plastic substrate after 16 h of culture, with an expression level superior to that of other differentiation markers such as bone, cartilage, muscle and fat. We conclude that C3H10T1/2 cells display a fibroblastic phenotype.

Gene expression profiles are similar in C3H10T1/2 cells seeded on two different substrates on the rigid scale in non-confluent conditions after 16 h of culture

The same density of C3H10T1/2 cells (11,110 cells/cm²) was plated on classic culture plastic plates and Uniflex Flexcell plates made of silicone substrate coated with type I collagen (Fig. 2A,B). Plastic substrate displays a Young Modulus of 1 GPa magnitude and is considered as extremely rigid. Uniflex Flexcell plates display a stiffness estimated at 5 MPa by the company (Flexcell International Corporation). The silicon substrate is 200-fold less rigid (5 MPa) compared to the plastic substrate (1 GPa) but is still considered as rigid on the micro-stiffness scale for substrates (Discher et al., 2009). C3H10T1/2 cells were harvested 16 h after plating at a non-confluent state (Fig. 2A,B) and a similar amount of mRNA was analyzed for gene expression. Tendon and other lineage marker expression profiles were similar in both substrate culture conditions (Fig. 2C,D). This shows that two substrates with different levels of stiffness on the rigid scale do not affect gene expression profiles in C3H10T1/2 cells seeded in non-confluent conditions for 16 h.

Differentiation potential of C3H10T1/2 cells cultured on plastic substrate over time

We investigated the tendon differentiation potential of C3H10T1/2 cells cultured on plastic substrate over time. Cells were plated on plastic culture plates at 11,110 cells/cm² density and left for 16 h, defined as day 0. C3H10T1/2 cells were let to grow for 14 days with no passage. C3H10T1/2 cells were harvested at 1 day, 7 days, 10 days and 14 days of culture. The cell density of C3H10T1/2 cells was measured (Fig. 3A,B) at each time point. At day 0 we obtained 17,100 cells/cm² (s.d. \pm 4885, $N=12$). Cells expanded until day 10 and reached a plateau from day 10 to day 14, defining two phases, one expansion phase until day 10 and a post-expansion phase after day 10 (Fig. 3B).

Lineage-specific gene expression analysis was conducted in order to assess the differentiation behavior of C3H10T1/2 cells cultured on plastic substrate over time. During the expansion phase (before day 10), *Scx*, *Colla1* and *Aqp1* genes displayed a continuous decrease of mRNA levels, while *Tnmd* mRNA levels displayed a bell shape with a maximum of twofold increase between day 1 and day 7 (Fig. 3C). During the post-expansion phase, *Scx* and

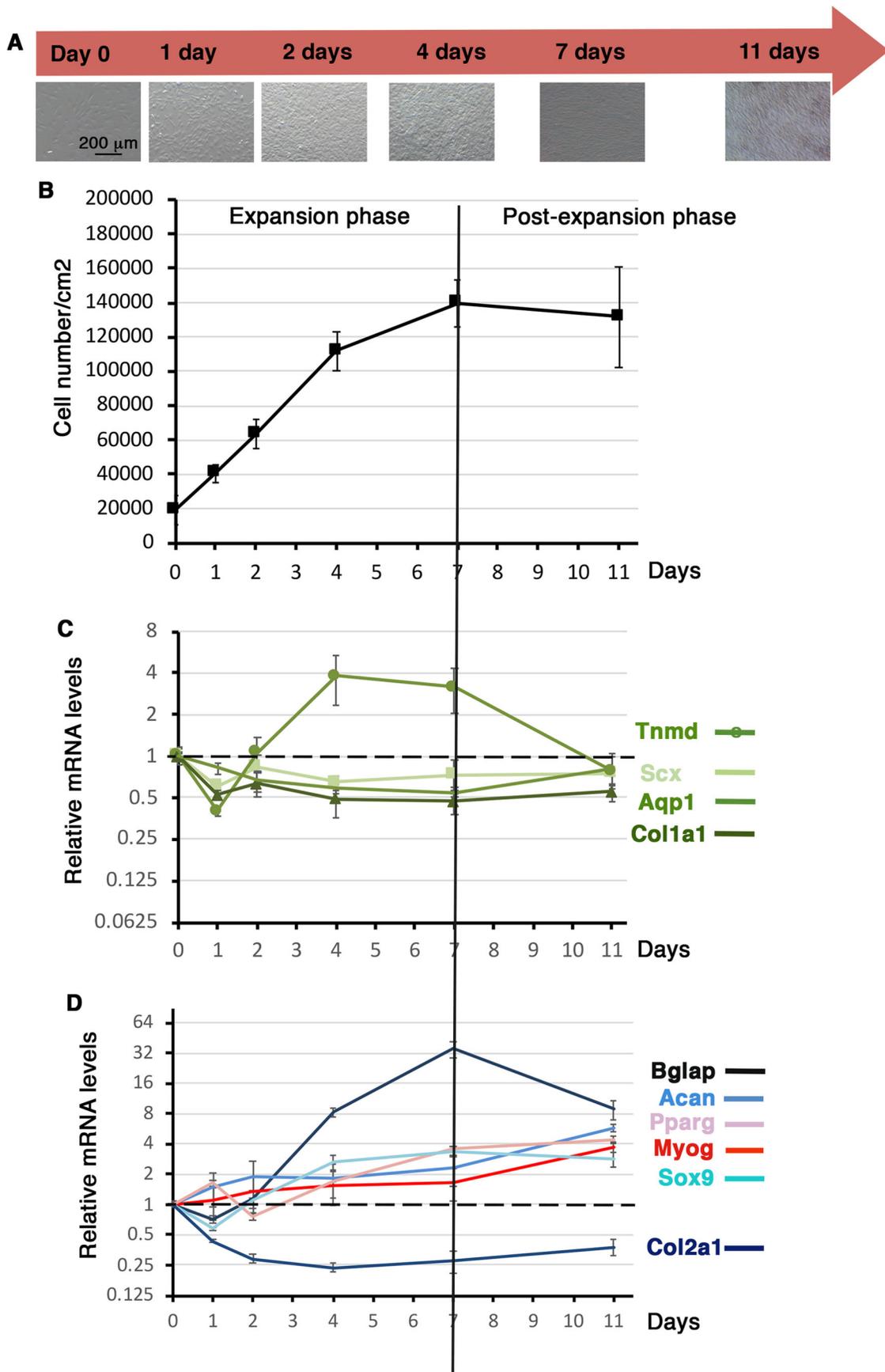


Fig. 4. See next page for legend.

Fig. 4. Gene expression in C3H10T1/2 cells cultured on silicone substrate over time. (A) C3H10T1/2 cells cultured on silicone substrate at different time points. 10^5 C3H10T1/2 cells were plated on Uniflex Flexcell plates made of silicone and coated with type I collagen, and left for 16 h to define the day 0 time point. Cells were then fixed at 1 day, 2 days, 4 days, 7 days and 11 days for RT-qPCR analyses. (B) Cell density or cell number/cm² was measured at each time point. (C,D) RT-qPCR analyses of the expression levels of tendon markers, *Scx*, *Tnmd*, *Col1a1*, *Aqp1* (C) and other cell lineage markers, *Bglap* (bone), *Sox9*, *Acan* and *Col2a1* (cartilage), *Myog* (muscle) and *Pparg* (fat) (D) in C3H10T1/2 cells cultured on silicone substrate at different time points. Gene mRNA levels were normalized to *Rplp0*. The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method using the T=0 condition as control. For each gene, the mRNA levels of the T=0 condition were normalized to 1. Graph shows means \pm s.d. of five biological samples for day 0 and of six biological samples for 1 day, 2 days, 4 days, 7 days and 11 days.

Tnmd expression decreased, while that of *Colla1* and *Aqp1* was stable (Fig. 3C). We also analyzed the expression of differentiation markers for other components of the musculoskeletal system, ranging from high to soft intrinsic tissue stiffness: bone (*Bglap*, *Pparg*), cartilage (*Sox9*, *Acan*), muscle (*Myog*) and fat (*Pparg*) (Fig. 3D). *Sox9*, *Acan* and *Myog* genes did not show any massive changes of expression over time (Fig. 3D), while the bone differentiation marker *Bglap* and the early fat differentiation marker *Pparg* displayed a striking increase of expression levels during the time of the culture (Fig. 3D). It has to be noted that these results were reported at the day 0 time point, when *Bglap* and *Pparg* were hardly expressed (Fig. 2C). These results show that confluence increased the expression of bone and fat differentiation markers in C3H10T1/2 cells cultured on plastic substrate over time.

We conclude that cell expansion to confluence has a global negative effect on the expression of *Scx*, *Colla1* and *Aqp1* tendon lineage markers, while promoting that of bone and fat markers in C3H10T1/2 cells cultured on plastic substrate.

Differentiation potential of C3H10T1/2 cells culture on silicon substrate over time

We next investigated the tendon differentiation potential of C3H10T1/2 cells cultured on silicon substrate over time. Similarly to cultures on plastic substrate, 10^5 cells were plated on the Uniflex Flexcell plates and left for 16 h, which was defined as day 0. Cells were then cultured for 1 day, 2 days, 4 days, 7 days and 11 days with no passage. The cell density of C3H10T1/2 cells was measured at each time point (Fig. 4A,B). At day 0 we obtained 19,298 cells/cm² (s.d. \pm 8 568, N=12) (Fig. 4B). C3H10T1/2 cells expanded until 7 days of culture on silicone substrate and then stopped growing to reach a plateau, defining the expansion and post-expansion phases (Fig. 4B).

Tendon gene expression analysis of C3H10T1/2 cells cultured on silicon substrate showed that the relative expression levels of all analyzed tendon genes, *Scx*, *Colla1*, *Tnmd* and *Aqp1* decreased (up to twofold) during the first day of culture compared to day 0 that was arbitrary normalized at 1 (Fig. 4C). The *Scx*, *Colla1* and *Aqp1* expression levels remained stable during the rest of the culture but below the day 0 expression levels (Fig. 4C). The relative mRNA levels of the differentiation tendon gene *Tnmd* increased again after day 1 and displayed a bell shape with a maximum of fourfold increase between 4 and 7 days during the expansion phase and a decrease during the post-expansion phase (7 days to 11 days) (Fig. 4C). This showed that the growing phase of C3H10T1/2 cells on silicone substrate was beneficial for *Tnmd* expression. As for plastic substrate, the bone marker *Bglap* displayed an increase of relative mRNA levels in C3H10T1/2 cells cultured on silicone

substrate during the expansion phase (35-fold increase at 7 days relative to T=0) and decreased during the post-expansion phase (Fig. 4D). The expression of the representative markers of differentiation for muscle (*Myog*) and fat (*Pparg*) displayed a progressive increase over time to reach fourfold at 11 days of culture (Fig. 4D). *Sox9* and *Acan* cartilage genes followed a similar pattern, while *Col2a1* displayed a decreased expression overtime (Fig. 4D), indicating an absence of cartilage differentiation.

We conclude that the expansion phase has a positive effect on *Tnmd* gene expression in C3H10T1/2 cells cultured on silicone substrate over time.

Tendon differentiation potential of C3H10T1/2 cells in a 3D-culture system

We next investigated the differentiation potential of C3H10T1/2 cells in a 3D-culture system.

We used the 3D-fibrin gel method to produce *in vitro*-engineered tendons (Gaut et al., 2016; Guerquin et al., 2013; Kapacee et al., 2010). This 3D-culture system is based on tension (Bayer et al., 2010) and has been extensively characterized for matrix production by tendon progenitor cells (Yeung et al., 2015). We engineered 3D-fibrin constructs with C3H10T1/2 cells (Fig. 5A–C). 3D-fibrin constructs took 5–7 days to fully form depending on the cultures (Fig. 5A). Day 0 was defined as when constructs were formed (Fig. 5A,B). Transverse sections to a 24-h construct show a homogeneous cell organization within the constructs (Fig. 5C). Longitudinal and transverse sections of 2-week-old constructs highlighted sustained homogeneous cell organization overtime (Fig. 5D). We compared tendon gene expression in C3H10T1/2 cells cultured in a 3D environment versus 2D plastic condition. The relative mRNA levels of *Scx* and *Colla1* were significantly increased in C3H10T1/2 cells cultured in 3D versus 2D conditions, while those of *Tnmd* were not after 10 days of cultures (Fig. 5E).

Tendon and cartilage gene expression was analyzed at different time points (day 0, day 2, day 4, day 7, day 11 and day 18). The day 0 time point corresponds to the day when the constructs were formed (Fig. 5A) and was the reference time point. The expression profile of tendon genes at day 0 in 3D-fibrin constructs (Fig. 5F) was similar to that in 2D-cultures (Figs 1C and 2C,D), i.e. relatively high levels of *Colla1* mRNAs compared to *Scx* and *Tnmd*. In contrast to a decrease in 2D-cultures (Figs 3 and 4), *Scx* and *Colla1* displayed an unchanged expression in 3D-fibrin constructs over time following that observed in day 0 (Fig. 5G). Similarly to 2D cultures (Figs 3C and 4C), *Tnmd* expression displayed a bell shape with a maximum of twofold increase between day 0 and day 7 in 3D-fibrin constructs (Fig. 5G). The cartilage genes, *Sox9* (progenitors), *Acan* and *Col2a1* (differentiated cells) were expressed at day 0 (Fig. 5H) and increased over time in 3D-fibrin constructs, indicating that the potential of C3H10T1/2 cells to differentiate into cartilage is maintained in 3D-fibrin constructs (Fig. 5I). The expression of *Pparg* (early fat differentiation marker) was above 32 cycles at day 7, indicating an absence of adipocyte differentiation of C3H10T1/2 cells in 3D-fibrin constructs.

We conclude that the 3D-environment in fibrin gel maintains tendon gene expression in C3H10T1/2 cells over time.

TGF β effect on tendon gene expression in C3H10T1/2 cells in 2D- and 3D-culture systems

The canonical TGF β /SMAD2/3 pathway is recognized to have a pro-tenogenic effect in cell cultures based on *Scx* expression (Guerquin et al., 2013; Havis et al., 2014, 2016; Lorda-Diez et al.,

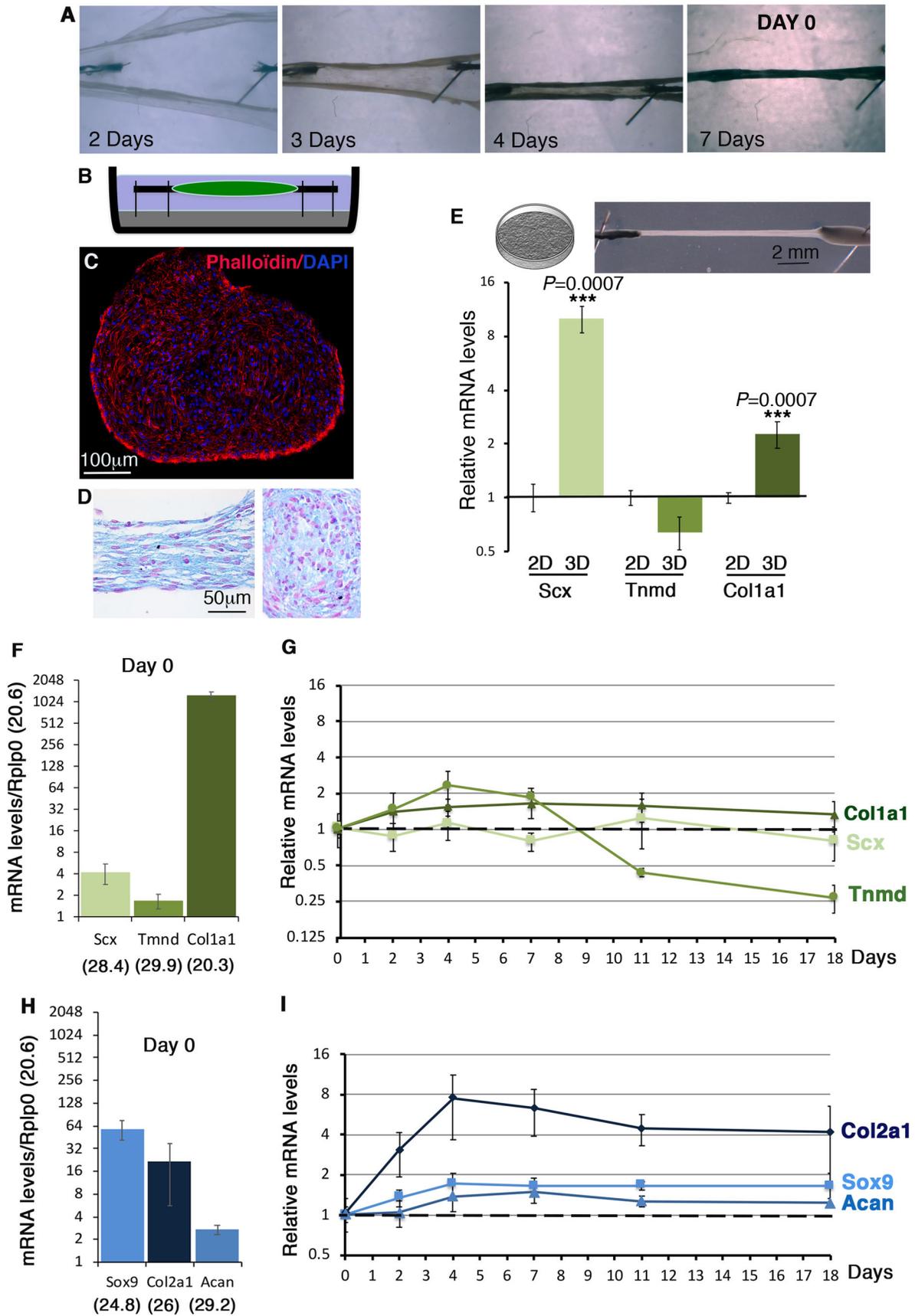


Fig. 5. See next page for legend.

Fig. 5. Tendon and cartilage gene expression in C3H10T1/2 cells in 3D-fibrin gel condition. (A) 3D-constructs were made by mixing C3H10T1/2 cells with a fibrin gel. 3–7 days were required to form a construct. Day 0 was considered when constructs were formed (shown here at 7 days). (B) Schematic representation of a 3D-fibrin construct. (C) Transverse section of a construct 24 h after formation labelled with DAPI and Phalloidin. (D) Hematoxylin and Eosin staining on longitudinal and transverse sections of constructs 2 weeks after formation. (E) Illustrations of 2D cultures and 3D-fibrin constructs that were used for RT-qPCR. RT-qPCR analyses of the expression levels for the *Scx*, *Tnmd* and *Col1a1* tendon genes in C3H10T1/2 cells cultured in 3D-fibrin constructs compared to 2D conditions on plastic for 10 days. The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method using the 2D conditions as controls. For each gene, the mRNA levels of 2D conditions were normalized to 1. The *P*-values were calculated using the Mann–Whitney test. (F–I) RT-qPCR analyses of the expression levels for *Scx*, *Tnmd* and *Col1a1* tendon genes (F,G) and *Sox9* and *Col2a1* cartilage genes (H,I) in C3H10T1/2 cells cultured in 3D-fibrin gel conditions over time, at day 0 ($N=4$), 2 days ($N=4$), 4 days ($N=4$) 7 days ($N=8$), 11 days ($N=4$) and 18 days ($N=4$). (F,H) At day 0, the means of the Cts (obtained from 500 ng of mRNA) are indicated in brackets for each gene. For each gene, the ΔCts were calculated using *Rplp0* as a reference gene. $\Delta Ct = Ct \text{ gene} - Ct \text{ Rplp0}$. The mRNA levels were reported using the $2^{-\Delta Ct}$ method. For each gene, $2^{-\Delta Ct}$ were multiplied per 10^3 in order to obtain values above 1. Graphs show means \pm s.d. of four biological samples. (G,I) RT-qPCR analyses of the relative expression levels of *Scx*, *Col1a1* and *Tnmd* tendon genes (G) and *Sox9*, *Col2a1* and *Acan* cartilage genes (I) in 3D-fibrin constructs over time. The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method using the day 0 condition as control. For each gene, the mRNA levels of day 0 condition were normalized to 1.

2009; Pryce et al., 2009). There are not many recognized transcriptional readout of TGF β activity, but *Smad7* is a negative-feedback regulator that is considered to be a general SMAD2/3 transcriptional target gene (Massagué, 2012). We assessed the activity of TGF β /SMAD2/3 signaling pathway with *Smad7* expression in C3H10T1/2 cells cultured with plastic and silicon substrates over time. The initial cycle threshold number for the *Smad7* gene ($Ct=23.9$ for plastic and $Ct=24.7$ for silicone) indicated that *Smad7* was expressed in C3H10T1/2 cells, in both substrate culture conditions at day 0. The *Smad7* expression profile displayed a mirror image to that of *Tnmd*, while *Smad7* expression followed that of *Scx* in C3H10T1/2 cells cultured in plastic and silicon substrate 2D-conditions (Figs 6A,B, 4C and 3C). The *Smad7* expression profile also mapped that of *Scx* and differed from that of *Tnmd* in 3D-fibrin constructs (Figs 6C and 5E). The expression profiles of *Tnmd* and *Scx* genes in Figs 3C, 4C and 5E have been added in Fig. 6A–C to facilitate comparison with *Smad7* expression levels. The fact that the activity of the TGF β /SMAD2/3 signaling pathway followed that of *Scx* expression in C3H10T1/2 cells whatever the culture system was consistent with the recognized positive regulation of *Scx* expression by the TGF β /SMAD2/3 signaling pathway in C3H10T1/2 cultures (Guerquin et al., 2013; Havis et al., 2014, 2016). The opposite direction of *Tnmd* and *Smad7* expression profiles in C3H10T1/2 cells (Fig. 6A–C) suggested that active TGF β /SMAD2/3 signaling pathway downregulated *Tnmd* expression.

In order to test this, we analyzed the effect of TGF β 2 on *Tnmd* expression in C3H10T1/2 cells seeded at two different cell densities, 11,110 cells/cm² (Fig. 6D) and 1110 cells/cm² (Fig. 6E). TGF β 2 treatment drastically decreased *Tnmd* mRNA levels, while increasing those of *Scx* in C3H10T1/2 cells compared to no treatment, in both seeding cell densities (Fig. 6D,E). Other tendon markers such as *Col1a1*, *Aqp1* and *Thbs2* did not display any significant variations upon TGF β 2 exposure, indicating a differential effect of TGF β on *Scx* and *Tnmd* expression in C3H10T1/2 cells in 2D-culture conditions. In similar culture

conditions, we already showed that *Sox9* expression was drastically decreased in TGF β 2-treated C3H10T1/2 cells (Havis et al., 2014). In order to test if the negative effect of TGF β 2 on *Tnmd* expression was inherent to the 2D-culture system, we also applied TGF β 2 in C3H10T1/2 cells cultured in 3D-fibrin gel. TGF β 2 was added in the culture medium of tendon constructs for 24 h and compared to non-treated constructs harvested at the same time. No apparent differences could be observed in the morphology of the TGF β 2-treated constructs when compared to controls (Fig. 6F). Consistent with the results obtained in 2D-cultures (Fig. 6D,E), we found an increase in the expression of *Scx* and a concomitant decrease in *Tnmd* expression in TGF β 2-treated 3D-tendon constructs compared to control constructs (Fig. 6G). *Col1a1* expression was increased, as was that of *Scx*, while *Aqp1* and *Thbs2* expression was decreased, as was that of *Tnmd* upon TGF β 2 exposure (Fig. 6G). The expression of cartilage genes was decreased (*Sox9* and *Acan*) or not changed (*Col2a1*) upon TGF β 2 exposure (Fig. 6G), indicating an absence of cartilage differentiation upon TGF β 2 exposure. This shows that TGF β 2 has a negative effect on *Tnmd* expression, while having a positive effect on *Scx* expression in C3H10T1/2 cells cultured in 3D-culture conditions.

We conclude that TGF β 2 is a negative regulator of *Tnmd* expression in C3H10T1/2 cells in 2D- and 3D-culture systems.

DISCUSSION

In the present study, we analyzed the tendon differentiation potential of C3H10T1/2 cells cultured in different conditions. Our results show that C3H10T1/2 cells behave differently for tendon gene expression depending on the substrate on which they were seeded in 2D cultures and 3D environment. We also identified TGF β 2 as a potent negative regulator of the tendon differentiation marker *Tnmd* in C3H10T1/2 cells in 2D- and 3D-culture systems.

Tendon differentiation potential for C3HT101/2 cells cultured on plastic and silicon substrates

C3H10T1/2 cells, although they express tendon genes in 2D-cultures (Fig. 1), are not preferentially committed to the tendon lineage as compared to primary tendon or ligament cells originating from native tissues. We found that the initial tendon gene profile was similar in C3H10T1/2 cells seeded on silicone and plastic substrate in non-confluent 2D conditions (Fig. 2). However, the silicone substrate was more prone to maintain the tendon phenotype of C3H10T1/2 cell cultures during the expansion and post-expansion phases over time compared to plastic substrate (Figs 3 and 4). A way to compare substrates of different chemical composition is to look at their stiffness. The design of our study allowed us to compare two substrates, plastic (1 GPa magnitude) and silicone (5 MPa) with a 200-fold difference in stiffness on the rigid scale. The extreme rigidity of plastic substrate (1 GPa) progressively decreases the expression of *Scx*, while a relatively less rigid substrate (5 MPa) decreases *Scx* and *Col1a1* by twofold in 1 day but then maintains their expression over time. The silicon substrate favors the expression of the tendon differentiation marker, *Tnmd* during the expansion phase. Based on *Scx* and *Tnmd* expression, we conclude that a substrate of 5 MPa rigidity favors the tendon phenotype in C3H10T1/2 cells over time. Although the stiffness values of both substrates display a 200-fold difference, these two substrates are still in the rigid scale favorable for bone differentiation (Discher et al., 2009). Consistently, C3H10T1/2 mesenchymal stem cells cultured on these two substrates (plastic and silicone) display a significant and drastic increase in the expression of the bone differentiation marker (*bglap*) over time. Because there was no addition of bone

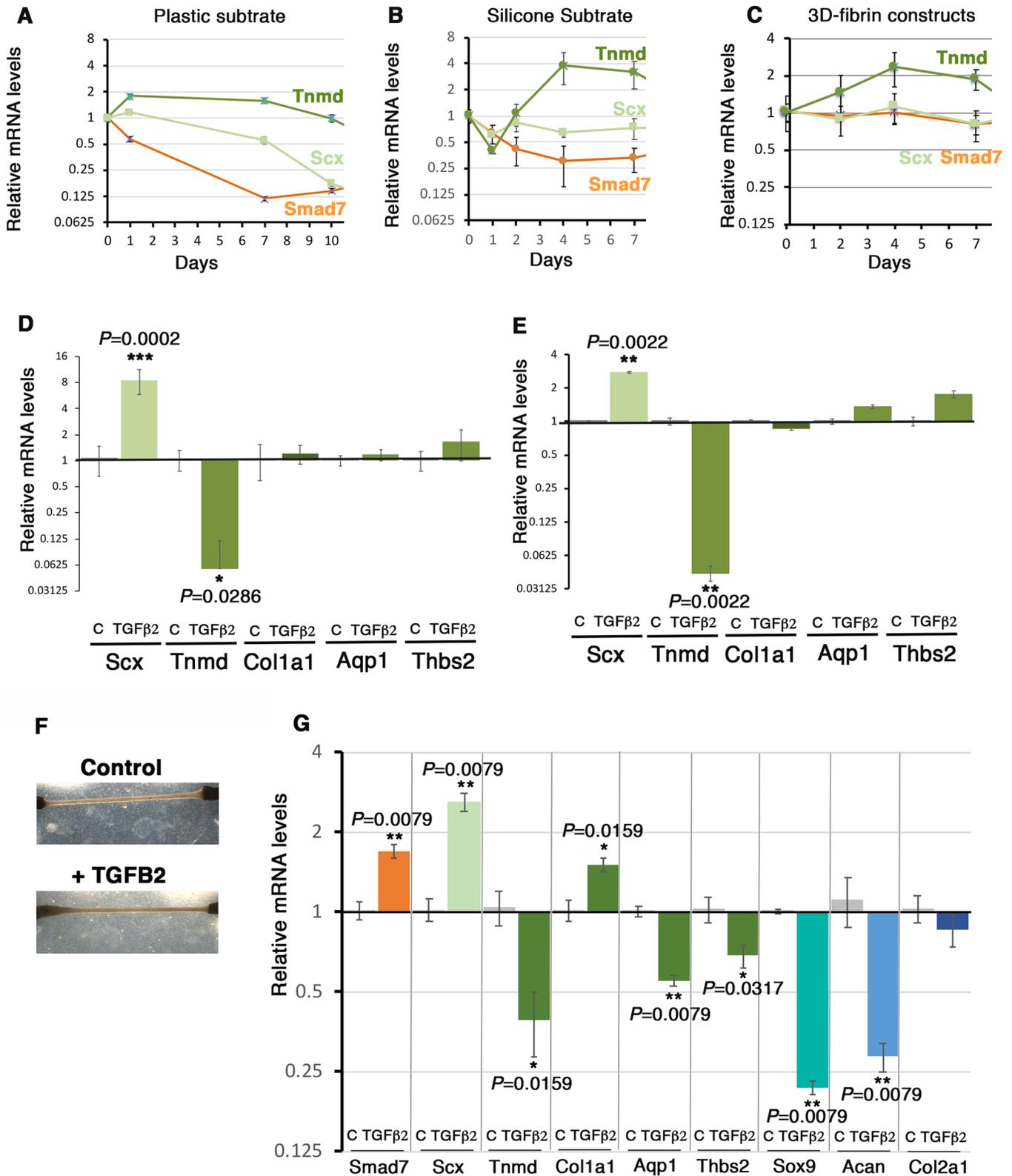


Fig. 6. See next page for legend.

differentiation medium in the culture conditions, we believe that cell confluence favors bone differentiation of C3H10T1/2 cells cultured on these two rigid substrates. The dramatic increase in the expression of the early differentiation fat marker *Pparg* in plastic

substrate (high stiffness) is counterintuitive with the range of soft stiffness known to promote fat differentiation (Discher et al., 2009). We interpret the ability of C3H10T1/2 cells to differentiate towards the fat lineage under a stiff substrate by the fact that C3H10T1/2

Fig. 6. Antagonistic effect of TGF β 2 on *Tnmd* and *Scx* expression in C3H10T1/2 cells in 2D- and 3D-culture systems. (A–C) RT-qPCR analyses of the expression levels of *Smad7* gene in C3H10T1/2 cells cultured upon plastic (A) and silicone (B) substrates during the expansion phase or cultured in 3D-fibrin gel condition (C). The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method. For each gene, the mRNA levels of the day 0 condition were normalized to 1. (A,C) Graphs show means \pm s.d. of four biological samples. (B) Graph shows means \pm s.d. of five biological samples. The expression profiles of *Scx* and *Tnmd* shown in Figs 3C, 4C and 5F have been plotted on panels A–C to facilitate comparison with *Smad7*. (D,E) RT-qPCR analyses of the expression levels of tendon gene expression in C3H10T1/2 cells cultured in control or TGF β 2-supplemented media and seeded at 10^5 cells (11,110 cells/cm 2) (D) and 10^4 cells (110 cells/cm 2) (E). Graphs show mean \pm s.d. of six biological samples. The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method. For each gene, the mRNA levels of control conditions were normalized to 1. (F,G) 3D-fibrin constructs in control or TGF β 2-supplemented media. (F) Images showing no significant variations in the morphology of the TGF β 2-treated 3D constructs (bottom) compared to control (top). (G) RT-qPCR analysis of the relative expression of the tendon-associated genes and cartilage-associated genes (*Sox9*, *Acan*, *Col2a1*) in 3D constructs treated or not treated with TGF β 2. Graph shows mean \pm s.d. of six biological samples. The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method. For each gene, the mRNA levels of control conditions were normalized to 1. *P*-values were calculated using the Mann–Whitney test.

cells make multilayers upon confluence. One obvious hypothesis is that cells expressing *Pparg* at 14 days of culture could be those in the superficial cell multilayer, not in contact with the plastic substrate and thus creating a soft environment.

TGF β is a potent negative regulator of *Tnmd* expression in C3H10T1/2 cells in 2D- and 3D-culture systems

Our work identifies a striking inverse correlation between *Tnmd* expression and TGF β activity (assessed with *Smad7* expression) in C3H10T1/2 cells cultured in 2D conditions on both plastic and silicone substrates and in 3D-fibrin gel systems over time. Consistently, TGF β 2 drastically decreases *Tnmd* expression, while promoting that of *Scx* in C3H10T1/2 cells cultured in 2D- and 3D-culture systems. The opposite behavior of *Scx* and *Tnmd* expression in cell cultures over time and upon TGF β application could reflect different steps of tenogenesis, with a progenitor step revealed by *Scx* and a differentiation one by *Tnmd*. During development, *Scx* is expressed before *Tnmd* and it has been shown that *Scx* is required and sufficient for *Tnmd* expression in developing tendons (Murchison et al., 2007; Shukunami et al., 2006). *Scx* and *Tnmd* also display opposite expression profiles in primary tendon cells over time (Shukunami et al., 2018). Moreover, *Scx* has been recently shown to directly regulate *Tnmd* transcription in primary tendon cells (Shukunami et al., 2018). The absence of *Tnmd* activation concomitant with *Scx* increase upon TGF β application (Fig. 6D–F) is unexpected but indicates that TGF β inhibits *Tnmd* expression in C3H10T1/2 cells in 2D- and 3D-culture conditions. It has to be noted that TGF β 2 increased the expression of both *Scx* and *Tnmd* genes in chick and mouse limb explants (Havis et al., 2014, 2016), in high-density cultures of chick limb cells (Lorda-Diez et al., 2009) or in 3D-culture systems made of human tendon cells (Bayer et al., 2010). We cannot exclude that the negative regulation of TGF β on *Tnmd* expression is cell-type specific and related to mesenchymal stem cells. The relevance to the *in vivo* situation of *Tnmd* inhibition by TGF β 2 in C3H10T1/2 cells requires further investigation.

Conclusion

This study shows that culture conditions such as expansion, confluence, substrates, and 2D and 3D environment affect the

tendon differentiation potential of a murine cell line of mesenchymal stem cells, C3H10T1/2 cells. We also identify TGF β 2 as a negative regulator of *Tnmd* expression in C3H10T1/2 cells in 2D- and 3D-culture systems. The identification of the optimum conditions that induce tendon cell differentiation *in vitro* is of particular interest for optimization of tendon cell culture protocols from stem cells that can be used for tendon repair.

MATERIALS AND METHODS

Tendon isolation from adult mice

C57BLj wild-type mice were purchased from Janvier (France). Achilles tendons were isolated from five wild-type mice at 5 months of age. The two Achilles tendons of the same mice were pooled to form one biological sample and processed for RT-qPCR analysis.

Cell cultures

The multipotent mouse mesenchymal stem cells, C3H10T1/2 cells (Reznikoff et al., 1973), were cultured on six-well TPP plastic culture plates (Merck) or six-well Uniflex Flexcell plates (FlexCell Int) made of silicone substrate coated with type I collagen, in Dulbecco's Modified Eagles Medium (DMEM, Invitrogen) supplemented with 10% fetal bovine serum (FBS, Sigma-Aldrich) 1% penicillin-streptomycin (Sigma-Aldrich), 1% glutamin (Sigma-Aldrich) and incubated at 37°C in humidified atmosphere with 5% of CO $_2$. The culture medium was changed every 48 h.

To study the effect of cell number on tendon gene expression, 0.5×10^5 (5555 cells/cm 2), 10^5 (11,110 cells/cm 2) and 2×10^5 (22,220 cells/cm 2) C3H10T1/2 cells were seeded in 9 cm 2 six-well TPP tissue culture plates (plastic substrate), left for 16 h in culture and analyzed for tendon gene expression by RT-qPCR. 250 ng of RNA were extracted from each sample before proceeding with RT-qPCR. To study of the effect of the initial cell number, six samples ($N=6$) were analyzed in each cell density condition. The *Rplp0* gene was used as the reference gene.

For the analysis of the differentiation potential of C3H10T1/2 cells seeded on plastic substrate, 10^5 cells were seeded in six-well TPP culture plates (11,110 cells/cm 2) and left for 16 h in culture. This defined day 0 ($N=4$) and then cells were cultured for another 24 h (1 day) ($N=4$), 7 days ($N=4$), 10 days ($N=5$) and 14 days ($N=4$). 500 ng of RNA were extracted from each sample before proceeding with RT-qPCR.

For analysis of the differentiation potential of C3H10T1/2 cells seeded on silicon substrate coated with type I collagen, 10^5 cells were seeded in six-well Uniflex Flexcell plates and left for 16 h in culture. This defined day 0 ($N=5$), then cells were cultured for another 24 h (1 day) ($N=6$), 48 h (2 days) ($N=6$), 7 days ($N=6$) and 11 days ($N=6$). 500 ng of RNA were extracted from each sample before proceeding with RT-qPCR.

3D-engineered tendon constructs in fibrin gels

3D fibrin-based tendon-like constructs made of mouse C3H10T1/2 cells were performed as previously described (Kapacee et al., 2008). Briefly, for each construct, 400 μ l of cell suspension (7.5×10^5 cells) were mixed with 20 mg/ml fibrinogen (Sigma-Aldrich) and 200 U/ml thrombin (Sigma-Aldrich). The fibrin gels containing cells were seeded in prepared SYLGARD-covered wells (DowChemical, Midland, MI, USA), in which two 8 mm sutures (Ethicon, Sommerville, NJ, USA) were pinned 10 mm apart. Culture medium containing 200 μ M of L-ascorbic acid 2-phosphate was added to the wells and gels were scored every day for a proper contraction into a linear construct. After 5–7 days, the C3H10T1/2 cells formed continuous tendon-like constructs between the two anchors. This was considered day 0. Each tendon construct was considered as a biological sample. The mRNA levels of each construct were analyzed by q-RT-PCR at 2 days, 4 days, 7 days, 11 days and 18 days after day 0.

TGF- β treatment on 2D and 3D cultures

10^5 or 10^4 C3H10T1/2 cells were plated on six-well TPP culture plates (plastic) and grown for 40 h. Then, human recombinant TGF β 2 (RD System) was applied at 20 ng/ml to C3H10T1/2 cells for 24 h. Cells were grown for another 24 h without TGF β 2 supplementation in the medium. Control cells were treated with Bovin Serum Albumin and HCl (BSA-HCl) in the same

Table 1. Primers used for RT-qPCR

Gene	Forward primers	Reverse primers	Accession no.
<i>Acan</i>	5'-CGCTGCAGTGATCTCAGAAGAAGT-3'	5'-TCACGCTCAGTAGTTGTCATGGT-3'	NM_001361500.1
<i>Aqp1</i>	5'-CAATTCACCTTGGCCGCAATGACC-3'	5'-TACCAGCTGCAGATGCCAATGA-3'	NM_007472.2
<i>Bglap</i>	5'-GCCTTCATGTCCAAGCAGGA-3'	5'-GCGCCGGAGTCTGTTCACTA-3'	NM_007541.2
<i>Cebpb</i>	5'-CGCCTTTAGACCCATGGAAG-3'	5'-AGGACCTCGGGCTCGTAGTAG-3'	NM_009883
<i>Col1a1</i>	5'-TGGAGAGAGCATGACCGATG-3'	5'-GAGCCCTCGCTTCCGACT-3'	NM_007742
<i>Col2a1</i>	5'-GGGCAACAGCAGGTTACAT-3'	5'-TGTTTCGTGCAGCCATCCT-3'	NM_001113515.2
<i>Myog</i>	5'-CACTGGAGTTCGGTCCCAAC-3'	5'-TGGGCGTCTGTAGGGTCAG-3'	NM_031189.2
<i>Pparg</i>	5'-TCGCTGATGCACTGCCTATG-3'	5'-GAGAGGTCCACAGAGCTGATT-3'	NM_011146
<i>Rn18s</i>	5'-GGCGACGACCCATTCG-3'	5'-ACCCGTGGTCACCATGGTA-3'	NR_003278.3
<i>Rplp0</i>	5'-ACCTCCTTCTCCAGGCTTT-3'	5'-CTCCACCTTGTCTCCAGTC-3'	NM_007475.5
<i>Runx2</i>	5'-GGTCCCCGGGAACCAA-3'	5'-GGCGATCAGAGAACAACACTAGGTTT-3'	NM_001145920
<i>Scx</i>	5'-CCTTCTGCCTCAGCAACCAG-3'	5'-GGTCAAAGTGGGGCTCTCCGTGACT-3'	NM_198885.3
<i>Smad7</i>	5'-CAGCACTGCCAAGCATGGT-3'	5'-ACCGAAACGCTGATCCAAAG-3'	NM_001042660.1
<i>Sox9</i>	5'-AGTACCCGCATCTGCACAAC-3'	5'-CCTCCACGAAAGGGTCTCTTCT-3'	NM_011448.4
<i>Thbs2</i>	5'-AGGTGCATCTCAGAGAGTCACTTCA-3'	5'-CTGCAAACACGAGATGGACATTTCTGC-3'	NM_011581.3
<i>Tnmd</i>	5'-AACACTTCTGGCCGAGGTAT-3'	5'-AAGTGTGCTCCATGTCATAGGTTTT-3'	NM_022322.2

volume applied for TGF β 2 treatment. TGF- β 2-treated and non-treated C3H10T1/2 cells were then fixed and processed for qPCR assays to analyze gene expression. In each condition, four biological samples ($N=4$) were used.

3D tendon constructs were treated with TGF β 2 or with BSA-HCl (controls) at day 7 of culture for 24 h. In each condition, five biological samples ($N=5$) were used for qPCR analysis.

RNA isolation, reverse transcription and RT-qPCR

Total RNAs were extracted from 2D and 3D cell cultures: C3H10T1/2 cells were cultured on classic culture dishes at day 0, 1 day, 7 days, 10 days and 14 days; C3H10T1/2 cells were cultured on silicone substrate at day 0, 1 day, 2 days, 4 days, 7 days and 11 days; C3H10T1/2 cells were cultured in 3D fibrin gel conditions at day 0, 2 days, 4 days, 7 days, 11 days and 18 days; and TGF β 2-treated C3H10T1/2 cells were cultured in 2D and 3D conditions. Total RNA was isolated using the RNeasy mini kit (Qiagen) with 15 min of DNase I (Qiagen) treatment according to the manufacturer's protocol. For RT-qPCR analyses, 250 ng or 500 ng RNA was reverse-transcribed using the High Capacity Retrotranscription kit (Applied Biosystems). RT-qPCR PCR was performed using SYBR Green PCR Master Mix (Applied Biosystems) using the primers listed in Table 1. We used *rn18s* (also named 18S) and *Rplp0* (also named 36b4) as housekeeping genes. The *rn18s* and *Rplp0* genes did not show any variation in the different experimental conditions. The *Rplp0* gene is detected around a Ct (threshold cycle) of 19.5 for 250 ng of RNAs and around a Ct of 18.5 for 500 ng of RNAs. This result is consistent with the log $_2$ -linear plot of the PCR signal. A decrease of one cycle corresponds to a twofold increase of RNA (Livak and Schmittgen, 2001). The *rn18s* gene was detected at around 7.5 Ct for 500 ng of RNA. The relative mRNA levels were calculated using the $2^{-\Delta\Delta Ct}$ method (Livak and Schmittgen, 2001; Schmittgen and Livak, 2008). The ΔCt values were obtained by calculating the differences: Ct(gene of interest) – Ct(housekeeping gene) in each sample. $\Delta\Delta Ct$ values were obtained by calculating the differences between ΔCt (experimental condition) and the average of control ΔCt values. For the analysis of the relative mRNA levels of cells cultured over time in classic culture plates (plastic substrate), Uniflex Flexcell plates (silicone substrate) or 3D-fibrin condition, the values of the day 0 time points were considered as controls and were normalized to 1. For the relative mRNA level analysis in TGF β 2-treated cells in 2D or 3D conditions, the cells in the absence of TGF β 2 supplementation were considered as controls and were normalized to 1.

For the absolute quantification of gene expression, 16 h after plating 10^5 cells, Y-axes correspond to $2^{-\Delta Ct} \times 10^3$ against the *Rplp0* house keeping gene from 250 ng of RNA (Fig. 1C), to $2^{-\Delta Ct} \times 10^3$ against the *Rn18s* house keeping gene from 500 ng of RNA (Fig. 2C) and $2^{-\Delta Ct} \times 10^4$ against the *Rplp0* house keeping gene from 500 ng of RNA (Fig. 2D).

Statistical analyses

Results are shown as means \pm s.d. The exact number of independent biological samples (4–6) is reported for each experiment. RT-qPCR data

were analyzed with the non-parametric Mann-Whitney test with Graphpad Prism V6. The asterisks in histograms indicate P -values that was considered significant, * $P<0.05$, ** $P<0.01$, *** $P<0.001$.

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Competing interests

The authors declare no competing or financial interests.

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Author contributions

Conceptualization: M.M., D.D.; Methodology: L.G., M.-A.B., C.B., I.C., M.O.; Validation: M.-A.B., C.B., D.D.; Formal analysis: L.G., D.D.; Investigation: L.G.; Data curation: D.D.; Writing - original draft: D.D.; Writing - review & editing: M.M., D.D.; Supervision: M.M., D.D.; Project administration: D.D.; Funding acquisition: D.D.

References

- Abo-Aziza, F. A. M. and Zaki, A. A. (2017). The impact of confluence on bone marrow mesenchymal stem (BMMSC) proliferation and osteogenic differentiation. *Int. J. Hematol. Stem Cell Res.* **11**, 121-132.
- Alberton, P., Dex, S., Popov, C., Shukunami, C., Schieker, M. and Docheva, D. (2015). Loss of tenomodulin results in reduced self-renewal and augmented senescence of tendon stem/progenitor cells. *Stem Cells Dev.* **24**, 597-609. doi:10.1089/scd.2014.0314
- Bayer, M. L., Yeung, C.-Y. C., Kadler, K. E., Qvortrup, K., Baar, K., Svensson, R. B., Peter Magnusson, S., Krosgaard, M., Koch, M. and Kjaer, M. (2010). The initiation of embryonic-like collagen fibrillogenesis by adult human tendon fibroblasts when cultured under tension. *Biomaterials* **31**, 4889-4897. doi:10.1016/j.biomaterials.2010.02.062
- Bellas, E. and Chen, C. S. (2014). Forms, forces, and stem cell fate. *Curr. Opin. Cell Biol.* **31**, 92-97. doi:10.1016/j.cob.2014.09.006
- Buckingham, M. (2017). Gene regulatory networks and cell lineages that underlie the formation of skeletal muscle. *Proc. Natl. Acad. Sci. USA* **114**, 5830-5837. doi:10.1073/pnas.1610605114
- Caplan, A. I. (1991). Mesenchymal stem cells. *J. Orthop. Res.* **9**, 641-650. doi:10.1002/jor.1100090504
- Dex, S., Lin, D., Shukunami, C. and Docheva, D. (2016). TENOgenic MODULating INsider factor: systematic assessment on the functions of tenomodulin gene. *Gene* **587**, 1-17. doi:10.1016/j.gene.2016.04.051
- Dex, S., Alberton, P., Willkomm, L., Söllradl, T., Bago, S., Milz, S., Shakibaei, M., Ignatius, A., Bloch, W., Clausen-Schaumann, H. et al. (2017). Tenomodulin is required for tendon endurance running and collagen I fibril adaptation to mechanical load. *EBioMedicine* **20**, 240-254. doi:10.1016/j.ebiom.2017.05.003
- Discher, D. E., Mooney, D. J. and Zandstra, P. W. (2009). Growth factors, matrices, and forces combine and control stem cells. *Science* **324**, 1673-1677. doi:10.1126/science.1171643

- Docheva, D., Hunziker, E. B., Fässler, R. and Brandau, O. (2005). Tenomodulin is necessary for tenocyte proliferation and tendon maturation. *Mol. Cell. Biol.* **25**, 699-705. doi:10.1128/MCB.25.2.699-705.2005
- Engler, A. J., Sen, S., Sweeney, H. L. and Discher, D. E. (2006). Matrix elasticity directs stem cell lineage specification. *Cell* **126**, 677-689. doi:10.1016/j.cell.2006.06.044
- Gaut, L. and Duprez, D. (2016). Tendon development and diseases. *Wiley Interdiscip. Rev. Dev. Biol.* **5**, 5-23. doi:10.1002/wdev.201
- Gaut, L., Robert, N., Delalande, A., Bonnin, M.-A., Pichon, C. and Duprez, D. (2016). EGR1 regulates transcription downstream of mechanical signals during tendon formation and healing. *PLoS ONE* **11**, e0166237. doi:10.1371/journal.pone.0166237
- Guerquin, M.-J., Charvet, B., Nourissat, G., Havis, E., Ronsin, O., Bonnin, M.-A., Ruggiu, M., Olivera-Martinez, I., Robert, N., Lu, Y. et al. (2013). Transcription factor EGR1 directs tendon differentiation and promotes tendon repair. *J. Clin. Invest.* **123**, 3564-3576. doi:10.1172/JCI67521
- Havis, E., Bonnin, M.-A., Olivera-Martinez, I., Nazaret, N., Ruggiu, M., Weibel, J., Durand, C., Guerquin, M.-J., Bonod-Bidaud, C., Ruggiero, F. et al. (2014). Transcriptomic analysis of mouse limb tendon cells during development. *Development* **141**, 3683-3696. doi:10.1242/dev.108654
- Havis, E., Bonnin, M. M.-A., De Lima, J. J. E., Charvet, B., Milet, C. and Duprez, D. (2016). TGF β and FGF promote tendon progenitor fate and act downstream of muscle contraction to regulate tendon differentiation during chick limb development. *Development* **143**, 3839-3851. doi:10.1242/dev.136242
- Hsieh, C.-F., Yan, Z., Schumann, R., Milz, S., Pfeifer, C., Schieker, M. and Docheva, D. (2018). In Vitro comparison of 2D-cell culture and 3D-cell sheets of scleraxis-programmed bone marrow derived mesenchymal stem cells to primary tendon stem/progenitor cells for tendon repair. *Int. J. Mol. Sci.* **19**, 2272. doi:10.3390/ijms19082272
- Huang, A. H., Lu, H. H. and Schweitzer, R. (2015). Molecular regulation of tendon cell fate during development. *J. Orthop. Res.* **33**, 800-812. doi:10.1002/jor.22834
- Humphrey, J. D., Dufresne, E. R. and Schwartz, M. A. (2014). Mechanotransduction and extracellular matrix homeostasis. *Nat. Rev. Mol. Cell Biol.* **15**, 802-812. doi:10.1038/nrm3896
- Ivanovska, I. L., Shin, J.-W., Swift, J. and Discher, D. E. (2015). Stem cell mechanobiology: diverse lessons from bone marrow. *Trends Cell Biol.* **25**, 523-532. doi:10.1016/j.tcb.2015.04.003
- Kapacec, Z., Richardson, S. H., Lu, Y., Starborg, T., Holmes, D. F., Baar, K. and Kadler, K. E. (2008). Tension is required for fibroblast formation. *Matrix Biol.* **27**, 371-375. doi:10.1016/j.matbio.2007.11.006
- Kapacec, Z., Yeung, C.-Y. C., Lu, Y., Crabtree, D., Holmes, D. F. and Kadler, K. E. (2010). Synthesis of embryonic tendon-like tissue by human marrow stromal/mesenchymal stem cells requires a three-dimensional environment and transforming growth factor β 3. *Matrix Biol.* **29**, 668-677. doi:10.1016/j.matbio.2010.08.005
- Karsenty, G., Kronenberg, H. M. and Settembre, C. (2009). Genetic control of bone formation. *Annu. Rev. Cell Dev. Biol.* **25**, 629-648. doi:10.1146/annurev.cellbio.042308.113308
- Kilian, K. A., Bugarija, B., Lahn, B. T. and Mrksich, M. (2010). Geometric cues for directing the differentiation of mesenchymal stem cells. *Proc. Natl. Acad. Sci. USA* **107**, 4872-4877. doi:10.1073/pnas.0903269107
- Kuo, C. K., Marturano, J. E. and Tuan, R. S. (2010). Novel strategies in tendon and ligament tissue engineering: advanced biomaterials and regeneration motifs. *BMC Sports Sci. Med. Rehabil.* **2**, 20. doi:10.1186/1758-2555-2-20
- Liu, H., Zhang, C., Zhu, S., Lu, P., Zhu, T., Gong, X., Zhang, Z., Hu, J., Yin, Z., Heng, B. C. et al. (2015). Mohawk promotes the tenogenesis of mesenchymal stem cells through activation of the TGF β signaling pathway. *Stem Cells* **33**, 443-455. doi:10.1002/stem.1866
- Liu, C.-F., Samsa, W. E., Zhou, G. and Lefebvre, V. (2017). Transcriptional control of chondrocyte specification and differentiation. *Semin. Cell Dev. Biol.* **62**, 34-49. doi:10.1016/j.semcdb.2016.10.004
- Livak, K. J. and Schmittgen, T. D. (2001). Analysis of relative gene expression data using real-time quantitative PCR and the 2^{- $\Delta\Delta$ CT} method. *Methods* **25**, 402-408. doi:10.1006/meth.2001.1262
- Lorda-Diez, C. I., Montero, J. A., Martinez-Cue, C., Garcia-Porrero, J. A. and Hurlé, J. M. (2009). Transforming growth factors β coordinate cartilage and tendon differentiation in the developing limb mesenchyme. *J. Biol. Chem.* **284**, 29988-29996. doi:10.1074/jbc.M109.014811
- Maeda, T., Sakabe, T., Sunaga, A., Sakai, K., Rivera, A. L., Keene, D. R., Sasaki, T., Stavnezer, E., Iannotti, J., Schweitzer, R. et al. (2011). Conversion of mechanical force into TGF- β -mediated biochemical signals. *Curr. Biol.* **21**, 933-941. doi:10.1016/j.cub.2011.04.007
- Mammoto, T., Mammoto, A. and Ingber, D. E. (2013). Mechanobiology and developmental control. *Annu. Rev. Cell Dev. Biol.* **29**, 27-61. doi:10.1146/annurev-cellbio-101512-122340
- Marturano, J. E., Schiele, N. R., Schiller, Z. A., Galassi, T. V., Stoppato, M. and Kuo, C. K. (2016). Embryonically inspired scaffolds regulate tenogenically differentiating cells. *J. Biomech.* **49**, 3281-3288. doi:10.1016/j.jbiomech.2016.08.011
- Massagué, J. (2012). TGF β signalling in context. *Nat. Rev. Mol. Cell Biol.* **13**, 616-630. doi:10.1038/nrm3434
- Mendias, C. L., Gumucio, J. P., Bakhurin, K. I., Lynch, E. B. and Brooks, S. V. (2012). Physiological loading of tendons induces scleraxis expression in epitenon fibroblasts. *J. Orthop. Res.* **30**, 606-612. doi:10.1002/jor.21550
- Murchison, N. D., Price, B. A., Conner, D. A., Keene, D. R., Olson, E. N., Tabin, C. J. and Schweitzer, R. (2007). Regulation of tendon differentiation by scleraxis distinguishes force-transmitting tendons from muscle-anchoring tendons. *Development* **134**, 2697-2708. doi:10.1242/dev.001933
- Nourissat, G., Berenbaum, F. and Duprez, D. (2015). Tendon injury: from biology to tendon repair. *Nat. Rev. Rheumatol.* **11**, 223-233. doi:10.1038/nrrheum.2015.26
- Pittenger, M. F., Mackay, A. M., Beck, S. C., Jaiswal, R. K., Douglas, R., Mosca, J. D., Moorman, M. A., Simonetti, D. W., Craig, S. and Marshak, D. R. (1999). Multilineage potential of adult human mesenchymal stem cells. *Science* **284**, 143-147. doi:10.1126/science.284.5411.143
- Prockop, D. J. (1997). Marrow stromal cells as stem cells for nonhematopoietic tissues. *Science* **276**, 71-74. doi:10.1126/science.276.5309.71
- Pryce, B. A., Watson, S. S., Murchison, N. D., Staverosky, J. A., Dunker, N. and Schweitzer, R. (2009). Recruitment and maintenance of tendon progenitors by TGF signaling are essential for tendon formation. *Development* **136**, 1351-1361. doi:10.1242/dev.027342
- Ren, J., Wang, H., Tran, K., Civini, S., Jin, P., Castiello, L., Feng, J., Kuznetsov, S. A., Robey, P. G., Sabatino, M. et al. (2015). Human bone marrow stromal cell confluence: effects on cell characteristics and methods of assessment. *Cytotherapy* **17**, 897-911. doi:10.1016/j.jcyt.2015.03.607
- Reznikoff, C. A., Brankow, D. W. and Heidelberger, C. (1973). Establishment and characterization of a cloned line of C3H mouse embryo cells sensitive to postconfluence inhibition of division. *Cancer Res.* **33**, 3231-3238.
- Schiele, N. R., Marturano, J. E. and Kuo, C. K. (2013). Mechanical factors in embryonic tendon development: potential cues for stem cell tenogenesis. *Curr. Opin. Biotechnol.* **24**, 834-840. doi:10.1016/j.copbio.2013.07.003
- Schmittgen, T. D. and Livak, K. J. (2008). Analyzing real-time PCR data by the comparative C_T method. *Nat. Protoc.* **3**, 1101-1108. doi:10.1038/nprot.2008.73
- Schweitzer, R., Chung, J. H., Murtaugh, L. C., Brent, A. E., Rosen, V., Olson, E. N., Lassar, A. and Tabin, C. J. (2001). Analysis of the tendon cell fate using Scleraxis, a specific marker for tendons and ligaments. *Development* **128**, 3855-3866.
- Schweitzer, R., Zelzer, E. and Volk, T. (2010). Connecting muscles to tendons: tendons and musculoskeletal development in flies and vertebrates. *Development* **137**, 2807-2817. doi:10.1242/dev.047498
- Shukunami, C., Takimoto, A., Oro, M. and Hiraki, Y. (2006). Scleraxis positively regulates the expression of tenomodulin, a differentiation marker of tenocytes. *Dev. Biol.* **298**, 234-247. doi:10.1016/j.ydbio.2006.06.036
- Shukunami, C., Takimoto, A., Nishizaki, Y., Yoshimoto, Y., Tanaka, S., Miura, S., Watanabe, H., Sakuma, T., Yamamoto, T., Kondoh, G. et al. (2018). Scleraxis is a transcriptional activator that regulates the expression of Tenomodulin, a marker of mature tenocytes and ligamentocytes. *Sci. Rep.* **8**, 3155. doi:10.1038/s41598-018-21194-3
- Takimoto, A., Oro, M., Hiraki, Y. and Shukunami, C. (2012). Direct conversion of tenocytes into chondrocytes by Sox9. *Exp. Cell Res.* **318**, 1492-1507. doi:10.1016/j.yexcr.2012.04.002
- Yao, L., Bestwick, C. S., Bestwick, L. A., Maffulli, N. and Aspden, R. M. (2006). Phenotypic drift in human tenocyte culture. *Tissue Eng.* **12**, 1843-1849. doi:10.1089/ten.2006.12.1843
- Yeung, C.-Y. C., Zeef, L. A. H., Lallyett, C., Lu, Y., Canty-Laird, E. G. and Kadler, K. E. (2015). Chick tendon fibroblast transcriptome and shape depend on whether the cell has made its own collagen matrix. *Sci. Rep.* **5**, 13555. doi:10.1038/srep13555
- Yoshimoto, Y., Takimoto, A., Watanabe, H., Hiraki, Y., Kondoh, G. and Shukunami, C. (2017). Scleraxis is required for maturation of tissue domains for proper integration of the musculoskeletal system. *Sci. Rep.* **7**, 45010. doi:10.1038/srep45010
- Zhang, Y.-J., Chen, X., Li, G., Chan, K.-M., Heng, B. C., Yin, Z. and Ouyang, H.-W. (2018). Concise review: stem cell fate guided by bioactive molecules for tendon regeneration. *Stem Cells Transl. Med.* **7**, 404-414. doi:10.1002/sctm.17-0206